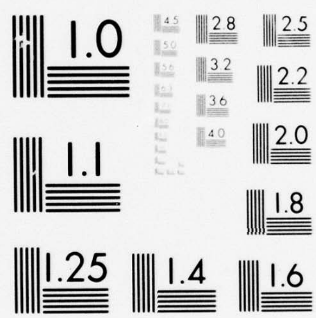
AD-A041 033 ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT COMM--ETC F/G 8/10
MARINE SEDIMENT PROPERTIES AND EMBEDMENT ANCHORS.(U)
NOV 76 D L JENKINS
UNCLASSIFIED MERADCOM-2195 NL

1 OF 1
AD
A041033

END
DATE
FILMED
7-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12 NW

Report 2195

MARINE SEDIMENT PROPERTIES AND EMBEDMENT ANCHORS

November 1976

Approved for public release; distribution unlimited.

U.S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 2195	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MARINE SEDIMENT PROPERTIES AND EMBEDMENT ANCHORS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) SP4 Douglas L. Jenkins		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Mobility Equipment Research and Development Command ATTN: DRDME-GF Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 1L762708AH67 Task 1L762708AH67FT
11. CONTROLLING OFFICE NAME AND ADDRESS Commander US Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia 22060		12. REPORT DATE November 1976
		13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) MERADCOM-2195		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

55p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Anchor Extraction
Anchor Holding Capacity
Anchor Penetration
Explosive Embedment Anchors
Marine Sediments
Sediment Properties

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The principal objective of this presentation is to provide a relatively complete compilation of the results of work that has been done in the areas of soil mechanics and marine sediment research. Only that data which could be more or less directly related to the design, use, and performance of explosive embedment anchors (EEA's) was used in this report.

(continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

403160

(Block 20 Cont'd)

The greater portion of the information that is used herein comes from research performed by the Naval Civil Engineering Laboratory, Port Hueneme, California; the United States Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, Virginia; and the United States Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.

The various physical properties of marine sediments are defined and described, and their significance to the performance of EEA's is discussed. The problems involved in accurately predicting the depth of penetration and the required extraction (pullout) forces for EEA's in marine sediment are covered in detail ~~(sections II and III)~~. Two methods for predicting penetration of EEA's in sediments are given ~~in section II~~.

The performance of the Army's XM-50 and XM-200 EEA's is reviewed and discussed briefly.

It is concluded from the information and data presented here that much more study and research is required in order to obtain a better understanding of the geomechanical behavior of marine sediments. This conclusion is not a new one, for it was evident in most of the publications and documents that were used as references in this presentation.

CONTENTS

ILLUSTRATIONS

TABLES

MARINE SEDIMENT PROPERTIES AND EMBEDMENT ANCHORS

I. INTRODUCTION

1. **Background.** The physical properties of marine sediments are not as simple as might be conjectured from a cursory observation. Geomechanical research has shown that a very complex interrelationship exists among these properties as they influence the physical behavior and performance of anchoring and mooring systems. Much of this complexity is yet to be understood completely, and until more study and research is done it is uncertain what properties are important enough to be considered in quantitative expressions of anchor penetration and extraction measurements.[1]

There have been numerous formulas developed over the years to quantitatively express or provide a means for a prediction of penetration and extraction values. These formulas have been developed for not only anchors in marine sediment but also, for the greater part, numerous other applications – not all of which are readily or directly useful in the study of embedment anchors.

2. **Objectives.** It is the purpose of this report to give a relatively complete and descriptive presentation of what is known about soil mechanics and marine sediment through research, especially in the relationships of marine sediment properties to the penetration and holding capacity of embedment anchors. The physical properties of marine sediment which most directly affect the penetration and/or extraction of embedment anchors will be covered in as much detail as possible.

3. **Physical Properties of Marine Sediments.** Grain or particle size is an obvious property that should be considered in almost any investigation of sediments. Grain size is important in that it has to some degree an influence upon all the other physical properties of marine sediments, therefore, it merits discussion in the description of physical properties of sediments as they relate to engineering and construction applications such as the design and use of embedment anchors.

A commonly used grain size scale, used widely by geologists, is the Wentworth Grade Scale (1922, after Udden, 1898) (adapted from ***Stratigraphy and Sedimentation,*** Second Edition, by W. C. Krumbein and L. L. Sloss. W. H. Freeman and Company. Copyright © 1963.):

---

[1] In this report, the term "sediment" is used throughout to refer to fluvial and marine bottom materials. Often, in other publications, the terms "soil" and "sediment" are used interchangeably; but in this presentation the term "sediment" is used to differentiate these materials from terrestrial soils. Also, it should be noted that the terms "extraction force" and "breakout force" as used herein can be considered synonymous.

Particle Name	Mean Diameter (mm)
Boulder	Above 256
Large cobble	256-128
Small cobble	128-64
Very large pebble	64-32
Large pebble	32-16
Medium pebble	16-8
Small pebble	8-4
Granule	4-2
Very coarse sand	2-1
Coarse sand	1-0.5
Medium sand	0.5-0.25
Fine sand	0.25-0.125
Very fine sand	0.125-0.0625
Coarse silt	0.0625-0.03125
Medium silt	0.03125-0.015625
Fine silt	0.015625-0.0078125
Very fine silt	0.0078125-0.00390625
Coarse clay	0.00390625-0.001953125
Medium clay	0.001953125-0.0009765625
Fine clay	0.0009765625-0.00048828125
Very fine clay	0.00048828125-0.000244140625
Colloid	0.000244140625 or less

"A grade scale is a systematic division of a continuous range of sizes into classes of grades, and the Wentworth grade scale provides a means of standardizing terminology. Wentworth's scale is a geometric grade scale. Geometric grade scales are well adapted to the description of sediments because they give equal significance to size ratios, whether the ratio occurs in gravel, sand, silt, or clay."[2]

Another rather obvious property of marine sediments is the water content. "Water content, . . . , is the ratio, expressed as a percent, of the weight of water to the weight of oven dried (110° C) solids in a given sediment mass."[3] The water content of sediments is influenced by local drainage and current conditions and their effects upon the depositional environment. Water content is a controlling factor for the degree of cohesiveness or lack of it, the in-place unit density, the shear strength of the sediment, the viscosity of the material, and the amount of pore-water pressure.

---

2 From *Stratigraphy and Sedimentation*, Second Edition, by W. C. Krumbein and L. L. Sloss. W. H. Freeman and Company. Copyright © 1963. p. 96.

3 George H. Keller, "Shear Strength and Other Physical Properties of Sediments From Some Ocean Basins," *Civil Engineering In The Oceans* (ASCE Conference, San Francisco, California: September 6-8, 1967), p. 404.

"Wet unit weight or wet bulk density is the weight per unit of total volume of a sediment mass. Samples taken from the sea floor are sufficiently close to 100 percent saturation to allow use of the term saturated unit weight, which is the in-place bulk density. In general terms, marine sediments in most near shore areas have a wet unit weight range from 78 to 109 lb/ft^3."[4] Intuitively, one may surmise that the saturations of sediments in a given area will decrease with an increase in depth below the ocean bottom if the sediments have not been recently disturbed.

Ocean bottom material can be divided into four broad categories in terms of engineering properties: (1) Cohesive sediments, such as clay, which develop strength as a result of cohesion between the particles; (2) cohesionless sediments which develop strength primarily as the result of solid friction between the particles and the interlocking of particles; (3) mixed sediments in which the properties of bulk cohesion and friction exist; and (4) coral or rock (massive) bottoms. Theoretically, many sediment problems are treated in terms of purely cohesive or cohesionless properties, while in nature mixed properties are most commonly encountered.[5]

In the following discussion of the shear strength of sediments, the above mentioned categories will be considered and described. Cohesive and cohesionless categories will be covered in greater detail because they are the most common. Mixed sediments have properties of both cohesive and cohesionless sediments, and they will be mentioned in later portions of this report. Coral and rock bottoms do not readily render themselves to quantitative description, and they will be only briefly described. The two most important categories are given in Figure 1.

"Shear strength of a cohesive sediment is a function of the cohesion and internal friction of the material and the effective stress normal to the shear plane, more simply expressed as:

$$S = c + p \tan \phi \text{ (Coulomb's equation)}$$

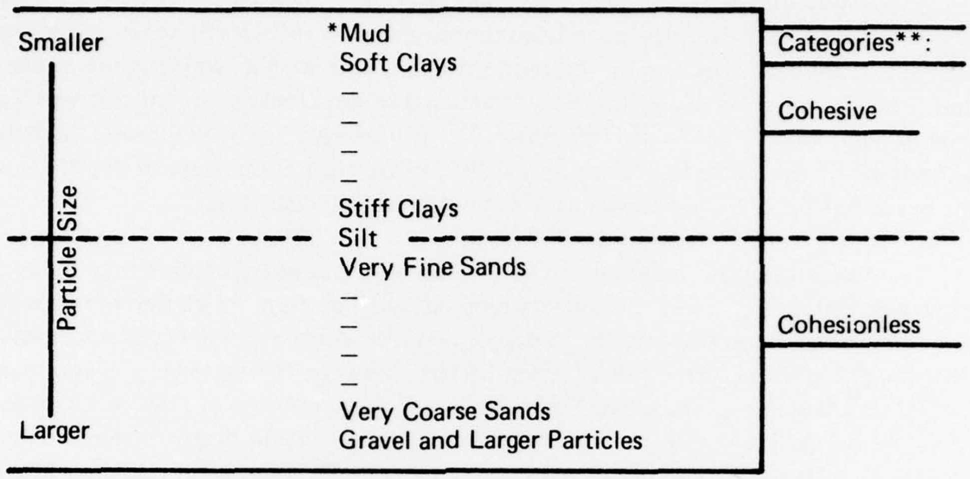
where C is the cohesion, p is the effective stress and ϕ is the angle of internal friction. Fine grained, saturated sediments stressed without loss of pore water behave with respect to the applied load as if they were cohesive materials without any internal friction ($\phi = 0$). In this instance, shear strength then is equal to cohesion ($S = c$)."[6] "In the case of cohesionless sediments, the shear strength can be expressed as:

---

4 George H. Keller, "Shear Strength and Other Physical Properties of Sediments from Some Ocean Basins," *Civil Engineering In The Oceans* (ASCE Conference, San Francisco, California: September 6-8, 1967), p. 406.

5 John A. Christians and Edward P. Meisburger, *Development of Multi-Leg Mooring System: Phase A-Explosive Embedment Anchor,* USAMERDC Report 1909-A, December 1967, p. 273.

6 George H. Keller, "Shear Strength and Other Physical Properties of Sediments from Some Ocean Basins," *Civil Engineering In The Oceans* (ASCE Conference, San Francisco, California: September 6-8, 1967), p. 399.



* The term "mud" will be defined later in this report under the behavior of cohesive sediments.

** Each category has its own unique characteristic physical-mechanical properties which differentiate it from the others. This becomes more apparent as each type of sediment is described.

Figure 1. Sediment categories.

$$S = (p - U_w) \tan \phi$$

wherein U_w is the initial pore-water pressure."[7] More detailed discussion of shear strength will be covered in a later portion of this report.

Shear strength ". . . values of less than 0.5 psi are often found in coastal areas where local drainage or current conditions strongly influence the depositioned environment. In these areas, minor changes in the environment can result in significant variations in the mass properties of the sediments."[8] As can be readily surmised from this statement, the shear strength of marine sediments cannot be assumed to be a constant and homogeneous property throughout any given body of sediment. This is one reason for the need for more research and study of sediment properties, and it is also a reason for being cautious in the application of quantitative expressions which may tend to overgeneralize the problem.

II. PENETRATION OF SEDIMENTS

4. Penetration Factors. The amount of penetration of marine sediments by an

[7] "Torsion Shear Tests and Their Place in the Determination of the Shearing Resistance of Soils, "*Soil Mechanics In Engineering Practice*, Karl Terzaghi and Ralph B. Peck, Eds., p. 85. Copyright © 1948 by John Wiley & Sons, Inc. Reprinted by permission.

[8] George H. Keller, "Shear Strength and Other Physical Properties of Sediments From Some Ocean Basins," *Civil Engineering In The Oceans* (ASCE Conference, San Francisco, California, September 6-8, 1967), p. 400.

embedment anchor is affected by the weight of the anchor in water, the velocity of the anchor, the shear strength of the sediment, and the amount of friction between the sediment and the penetrating anchor.

Due to the general lack of adequate research in this area, one major problem is that the role of velocity-dependent terms, or sediment viscosity, is not clearly understood.[9] "If velocity-dependent terms are important, the problem of predicting penetration becomes significantly more complex. Penetration prediction schemes based on easily measured index properties would be difficult to develop if such a complex concept as sediment viscosity needs to be considered. On the other hand, if static terms are most significant the development of such a scheme could be relatively simple. Also a survey penetrator would be of less value if the measured data included a complex combination of static and viscous quantities."[10]

D. G. True (1975) has established methods for estimating penetration of direct embedment anchors in cohesive (clay) and cohesionless (sand) sediments. Mathematical expressions for determining anchor penetration do not render adequate results in a closed-form solution. However, more readily usable information can be obtained through incremental techniques. The incremental form is given in the following:

$$v_{i+1} = v_{i-1} + \frac{W - F_i(v_i, z_i)}{M^* v_i} (2 \Delta z)$$

where

v_{i+1} = velocity at the depth being considered in ft/s (m/s)

v_{i-1} = velocity at two depth measurements above the depth being considered in ft/s (m/s)

W = buoyant weight of projectile in soil in lb (kg)

v_i = velocity calculated one depth increment above the depth being considered in ft/s (m/s)

$F_i(v_i, z_i)$ = resisting force at the depth and velocity one depth increment above the depth being considered = $F_i^* + F_{H_i}$ in lb (kg)

---

9 H. J. Migliore and H. J. Lee, *Seafloor Penetration Tests: Presentation and Analysis of Results*, Technical Note N-1178 (Naval Civil Engineering Laboratory, Port Hueneme, California; August 1971), p. 19.

10 *Ibid.*, pp. 19-20.

M^* = effective mass of penetrator; equals penetrator mass plus added mass in slugs (kg)

Δz = depth increment in ft (m)

F_i^* = soil resisting force = $C_{1_i} S_{u_i} S_{\dot{e}_i}$ in lb (kg)

F_{H_i} = fluid inertial drag force = $v_i^2 C_{2_i}$ in lb (kg)

S_{u_i} = undrained sediment shear strength in lb/ft^2 (kg/m^2)

S_{e_i} = ratio between dynamic and static shear strength

$= S_{\dot{e}_i}^*/\ell + [1/\sqrt{(C_{\dot{e}} V_i/S_{u_i} \ell_i) + C_o}]$

C_{1_i} = $N_c A_{F_i} + (\delta_i^*/S_{t_i}) A_{s_i}$ in ft^2 (m^2)

C_{2_i} = $(1/2) \rho_i C_D A_{F_i}$

$S^*_{\dot{e}}$ = maximum $S_{\dot{e}_i}$ at high velocity; equal to 5 for all soils

$C_{\dot{e}}$ = constant; equal to 20 for all clays and sands in $\frac{lb/ft^2}{sec}$ $\frac{kg/m^2}{sec}$

ℓ_i = effective length of shearing zone; equals depth of embedment or length of penetrometer body, whichever is smaller in ft (m)

C_o = dimensionless constant; equal to 0.04 for all clays and sands

N_c = deep bearing factor; equal to 9 for clays and sands

A_{F_i} = frontal area of penetrometer in ft^2 (m^2)

δ_i^* = adhesion reduction factor

S_{t_i} = soil sensitivity (ratio of remolded to undisturbed strength); use $S_{t_i} = 1$ for sands

A_{s_i} = side area of penetrometer in ft^2 (m^2)

ρ_i = mass density of soil in $slugs/ft^3$ (kg/m^3)

C_D = drag coefficient (estimated from fluid mechanics principles)[11]

[11] R. J. Taylor, D. Jones, and R. M. Beard, *Handbook For Uplift-Resisting Anchors*, Naval Civil Engineering Laboratory, Port Hueneme, California, September 1975, pp. 107-109.

In this incremental form, all functions are known except that $v_1 + 1, \Delta z$ is specified at one-twentieth or less of an estimated embedment depth. At the beginning, however, $v_1 = v_1$ is not known, and it is necessary to estimate v_1; this is done most directly by computing v_2 for $v_1 = v_0$ and, then, starting over again using $v_1 = \frac{v_0 + v_2}{2}$.

An equivalent direct relationship for this procedure is:

$$v_1 = v_0 - \frac{\Delta z}{v_0 M^*} \left(C_{2_1} v_0^2 + C_{1_1} S_{e_1} S_{V_1} - W \right).$$

A better estimate of an initial value v_1 will not give a better value of final depth z_n. A flow diagram of the calculation procedure for determining the momentum penetration in clay and sand is shown in Figure 2.

Another suggested prediction technique is outlined by Migliore and Lee.[12] The extent to which this procedure is applicable to the penetration of sediments by embedment anchors is uncertain until further study and research have been performed.

III. EXTRACTION FROM SEDIMENTS

5. The General Problem. The force required to extract an explosive embedment anchor (EEA) is dependent not only on the size of the anchor itself but also on the type of sediment or sediments involved, the length of time that the anchor has been embedded, the type(s) of loading condition(s), and the depth of embedment.

In order to more clearly differentiate between what is considered shallowly embedded and what should be considered deeply embedded, the following definition will prove useful:

"Deeply embedded anchors are defined as having a ratio of depth of embedment to anchor diameter equal to or greater than 5."[13]

---

[12] H. J. Migliore and H. J. Lee, *Seafloor Penetration Tests: Penetration and Analysis of Results,* Technical Note N-1178, Naval Civil Engineering Laboratory, Port Hueneme, California, August 1971.

[13] Bing C. Yen, *Deep Anchor Long-Term Model Tests,* CR 76.003, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1975, p. 1.

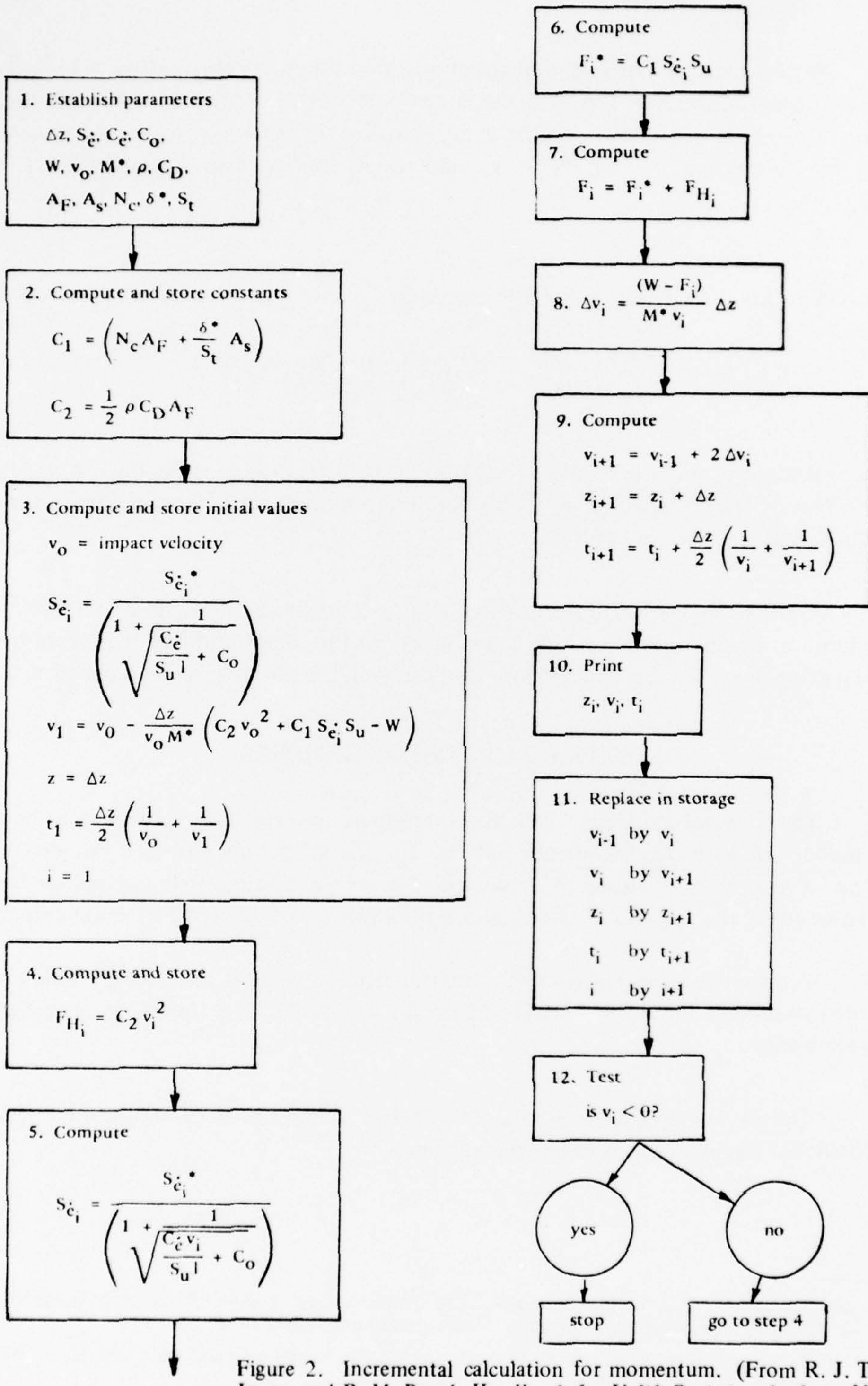


Figure 2. Incremental calculation for momentum. (From R. J. Taylor, D. Jones, and R. M. Beard, *Handbook for Uplift-Resisting Anchors*, Naval Civil Engineering Laboratory, Port Hueneme, California, September 1975, p. 109.)

The appendix presents an extract from a report by Aleksandar S. Vesic, in which is given a more comprehensive explanation of the determination of extraction forces.[14]

In Vesic's approach to this problem, the embedment anchor is assumed to be a centrally loaded object that is being extracted by a vertical force against a horizontal bottom. According to this method, the extraction force can be calculated from the following components: "(1) . . . the effective weight of the object (anchor), W; (2) the effective weight of the mass of sediment, $\overline{W}s$, involved in the extraction together with the object; (3) the vertical component, Rv, of the forces of shearing resistance, R, of the overburden sediment along the slip surface separating that part of the sediment involved in extraction from the rest of the sediment mass; (4) the vertical component, Ca, of forces of adhesion between the surface of the object and the adjacent sediment; and (5) the sediment suction force, Pw, resulting from differences in pore-water stresses above and below the object, caused by attempted vertical upward movement of the system."[15]

These controlling factors are described in greater depth in the appendix.

6. **Applicable Methods.** In addition to the approach mentioned in the appendix, a sizable number of other analytical methods have been developed; however, it seems reasonable to assume that those which deal with rectangular or similar shaped objects are the most useful and readily applicable in calculating the extraction forces of embedment anchors. Some methods tend to overgeneralize in that they are an attempt to arrive at a suitable formula which would fit all cases. These methods fail to consider the importance of either sediment properties, anchor configuration, or both. As this report points out, sediment properties can vary widely among the different sediment types. Logically, it seems that the most acceptable methods are those which address particular sediment types and/or specific anchor configurations.

7. **Long-Term Repeated (Cyclic) Load-Holding Capacity.** "Embedment anchor systems which are used to moor surface vessels or buoys will be subjected to a combination of sustained and repeated loads which will vary with the tautness of the system and the nature of wave or tidal action."[16]

---

14 Aleksandar S. Vesic, "Breakout Resistance of Objects Embedded in Ocean Bottom," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 97, No. SM9, Proc. Paper 8372, September 1971.

15 *Ibid.*, pp. 1186-1202.

16 R. J. Taylor and H. J. Lee, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 8.

Repeated, or cyclic, loading has its own special problems that must be considered in order to accurately determine the holding capacity of embedment anchors.

"In almost all cases failure occurs at a lower force level if a portion of the load is repeated . . . . There has been a good deal of research on the response of sediment to repeated loading. Most of this has consisted of applying repeated loads to cylindrical sediment samples in triaxial cells and determining the amount of strength reduction produced by different numbers of load repetitions . . . . No research has been conducted to determine how natural sediments respond to repeated loads extending for long periods of time. Since this may be the critical case for anchor loading, it is necessary to extrapolate the results from existing research."[17]

It has been found that ". . . virtually all sediments respond adversely to repeated loading. However, some sediments are affected more strongly than others. Lee and Fitton (1969) provided an indication of the influence that particle grain size has on the strength under repeated load conditions. Results show that sediments in the fine-sand to silt range are the most susceptible to repeated loading with clays, sands, and gravels being less susceptible."[18]

Terzaghi used the following equation to determine the ultimate bearing capacity of clays for rectangular anchor plates:

$$Qult = 2.85\ qu\ (1 + 0.3\ B/L),$$

where Qult = ultimate uplife resistance,
qu = the uncounted compressive strength of an undisturbed sample,
B = breadth of plate, and
L = length of plate.

"The commonly used equation for representing the holding capacities of embedment anchors is:

$$F_T = A(C\overline{N}_c + \gamma b\ D\overline{N}_q)\ (0.84 + 0.16\ B/L)$$

where
A = fluke area (ft^2)
C = sediment cohesion (psf), characteristics strength

[17] R. J. Taylor and H. J. Lee, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 8.

[18] *Ibid.*

γb	=	buoyant unit weight of sediment (pcf)
D	=	fluke embedment depth (ft)
$\overline{N}c$, $\overline{N}q$	=	holding capacity factors
B	=	fluke width (ft)
L	=	fluke length (ft)

"This equation is relatively general and can be applied to almost any form of loading. However, the loading capacity factors and the cohesion may vary with the loading mode, and they have been found to vary with sediment type, density, and relative anchor embedment depth, D/B (B is the fluke width). The major problem of estimating holding capacity is then one of estimating C, $\overline{N}c$, and $\overline{N}q$."[19]

Figure 3 is a block diagram showing the general procedural framework for predicting anchor holding capacity according to this equation.

8. **Behavior of Cohesive Sediments.** Included in this grouping of sediments are muds, clays, and some silts. The major determining factors in the degree of cohesiveness are the amount of pore water, the particle size, and the shape of particles involved.

Mud is a very ambiguous term often applied to soft sediments in general. For use in this report, it will be defined as a sediment which is highly saturated with water. It displays very little consolidation. It is varyingly cohesive, very fine grained, and is usually composed of clay-size particles of both mineral and/or organic origin.

A number of tests have been performed on cohesive sediments, but only a few are applicable to the study of their ability to hold embedment anchors. "A laboratory study of the repeated load response of anchors embedded in clay was conducted at the University of Massachusetts (Bemben and Kupferman, 1971). The results indicated a very complicated process of upward anchor displacement with time. However, the results do not appear sufficient for quantitative design of practical anchor systems. In general a reduction factor of about 50 percent of the short term capacity appears adequate for long-term repeated loading of anchors in cohesive sediment. It is suggested that this reduction factor be applied directly to other sediment when additional testing is not feasible."[20]

---

[19] R. J. Taylor, D. Jones, and R. M. Beard, *Handbook For Lift-Resisting Anchors*, Naval Civil Engineering Laboratory, Port Hueneme, California, September 1975, p. 112.

[20] R. J. Taylor and H. J. Lee, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 9.

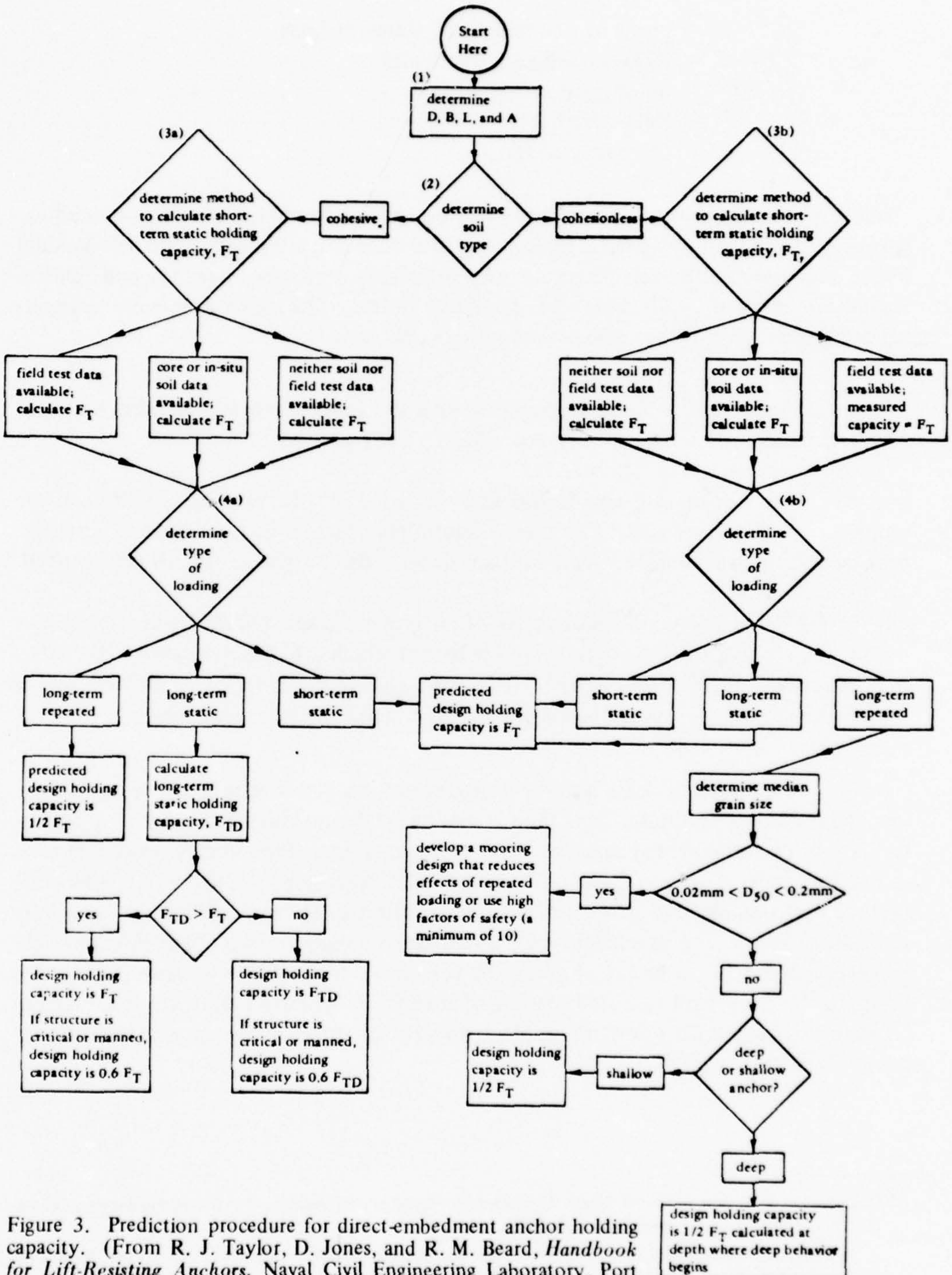


Figure 3. Prediction procedure for direct-embedment anchor holding capacity. (From R. J. Taylor, D. Jones, and R. M. Beard, *Handbook for Lift-Resisting Anchors*, Naval Civil Engineering Laboratory, Port Hueneme, California, September 1975, p. 113.)

Hvorslev (1948) gave the following expression for remolded clay which does not take into consideration the force of cohesion:

$$S = p \tan \phi,$$

wherein ϕ equals 28° to 30° (exceptionally, as low as 20°). The shear strength for all cohesive sediments is expressed in the equation:

$$S = c + p \tan \phi,$$

which is essentially the same as the former equation, except that the force of cohesion has been included.

9. **Behavoir of Cohesionless Sediments.** In this group of sediments are silts, sands, and gravels. The shear strength of cohesionless sediment is a function of the degree of compactness, the particle size and shape, and the angle of internal friction. Also, pore-water pressure is an important influencing factor in sediment strength.

The importance of sediment adhesion and suction forces decreases with increased grain size and greater amount of void space. Some fine silts may be transitional between cohesive and cohesionless sediments and, therefore, display characteristics of both types.

A fairly pure sand bottom can be considered to be saturated to some degree. This, of course, is dependent upon the local environment of the sediment. Sands are generally cohesionless; and the shear strength is expressed by Terzaghi and Peck[21] as: "$S = (p - U_w) \tan \phi$, wherein U_w is the initial pore-water pressure." (See Table 1.)

Table 1. Representative Values of ϕ for Dry Sands*

Packing	Round Grains (Uniform)	Angular Grains (Well Graded)
Loose	28.5°	34°
Dense*	35°	46°

* Average of peak values at normal stresses between 0 and 3 kg/cm². With increasing normal stresses, the value of ϕ is likely to decrease slightly. ("Torsion Shear Tests and Their Place in the Determination of the Shearing Resistance of Soils," *Soil Mechanics and Engineering Practice*, Karl Terzaghi and Ralph B. Peck, Eds., p. 82. Copyright © 1948 by John Wiley and Sons, Inc. Reprinted by permission.)

21 "Torsion Shear Tests and Their Place in the Determination of the Shearing Resistance of Soils," *Soil Mechanics in Engineering Practice*, Karl Terzaghi and Ralph B. Peck, Eds., p. 85, Copyright ©1948 by John Wiley & Sons, Inc. Reprinted by permission.

In the case of silts and silty sand, the shear strength is expressed by Terzaghi and Peck[22] as: "$S = (p - U_w) \tan \phi_{cq}$, wherein ϕ_{cq} is the slope angle, which can be as low as 17°, and values of between 20° and 22° are common."

The nature of the reduction of shear strength in sand with repeated load conditions is very complex. "Lee and Seed (1967) investigated the response of a uniform river sand, placed at several different relative densities and subjected to 10 load repetitions. The specimens, tested in unchained condition, had reductions ranging from 50 to 85 percent. In the same study, it is shown that 75 to 90 percent strength reductions occurred after 1000 cycles."[23]

This situation could be very dangerous. "However, one way in which the problem could become less severe would be through partial drainage. Evidence suggests that sand strength is decreased because of a buildup in pore water pressures. If these are not allowed to dissipate, the strength reduction will be extreme. In all field problems, however, at least some pore pressure dissipation will occur and therefore increase the repeated load strength. This then becomes a complex porous media flow problem which can be solved only through model and field test."[24]

In tests performed by Kalajian (1971) at the University of Massachusetts on a loose saturated fine to medium sand, ". . . the cyclic creep rate for shallow anchors was considerably less than the creep rate for deeply embedded anchors, probably because of partial dissipation of pore pressure and subsequent densification of the sand in the 'shallow' cases. For shallow anchors it was found that creep rates were negligible when the cyclic load was less than 50 percent of the static capacity.

" 'Deep' anchors failed at lower percentages of their respective static capacities. It is reasonable to assume, however, that in no case will the holding capacity of a 'deep' anchor be less than that of a 'shallow' anchor simply because the anchor must be pulled through the 'shallow' depth range before pullout."[25]

"Trofimenkov and Mariupolskii (1965) performed what are the only full-scale, repeated loading, pullout tests of anchors. In long-term repeated load tests on anchors embedded in fine to medium sands of loose medium density, the holding capacities were reduced by up to 50 percent."[26]

---

22 "Torsion Shear Tests and Their Place in the Determination of the Shearing Resistance of Soils," *Soil Mechanics in Engineering Practice*, Karl Terzaghi and Ralph B. Peck, Eds., p. 85, Copyright ©1948 by John Wiley & Sons, Inc. Reprinted by permission.

23 R. J. Taylor and H. J. Lee, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 9.

24 *Ibid.*, p. 9.

25 *Ibid.*, p. 10.

26 *Ibid.*, p. 10.

"The test series mentioned above are the only two known to have been performed on saturated sand where drainage was allowed. Although these results are very limited, at least some tentative design procedures can be developed based on them. For 'shallow' embedment, a maximum allowable cyclic load of 50 percent of the static or short-term capacity is recommended. For 'deep' embedment a conservative design should result if the applied cyclic load is less than 50 percent of the static capacity corresponding to the transition between 'deep' and 'shallow' behavior."[27]

It is possible that the required reduction factor may be greater with sediment in the silt-fine sand range. It is suggested that seafloor sediment grain size characteristics be determined whenever a direct-embedment anchor is to be established in granular sediment which will be subjected to repeated loadings. An anchor in granular sediment with a characteristic mean grain size ". . . greater than 0.20 mm should be designed with the respective loading factor given above. If the sediment falls in the silt fine sand range, between .02 mm – .20 mm, it may be necessary to use a different anchoring technique or employ high safety factors (a minimum of 10). Another possibility would be to reduce system tautness and thereby reduce the effect of surface wave action and dampen repetitive loading. The approach depends upon system requirements, system importance, and the consequences which would result from a failure."[28]

"There is little information available for a rational determination of the uplift resistance of a deeply embedded anchor plate in a cohesionless sand. Tang states that common practice is to assume that for large uplift loads the anchor resistance is due to the lifting of a 60-degree prism of sediment above the plate with the ultimate holding capacity dependent entirely on the weight of the sediment in the prism. This condition is shown in Figure 4. A second conventional practice used in the case of small loads has been to assume that the holding capacity is determined by shear strength operating along a surface rising vertically from the anchor perimeter as in Figure 5 with

$$F = 0.4\gamma \tan \phi A$$

where F = uplift capacity
γ = unit weight of sediment
A = total surface rising from the anchor perimeter
ϕ = friction angle

---

27 R. J. Taylor and H. J. Lee, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 10.

28 *Ibid.*, p. 10.

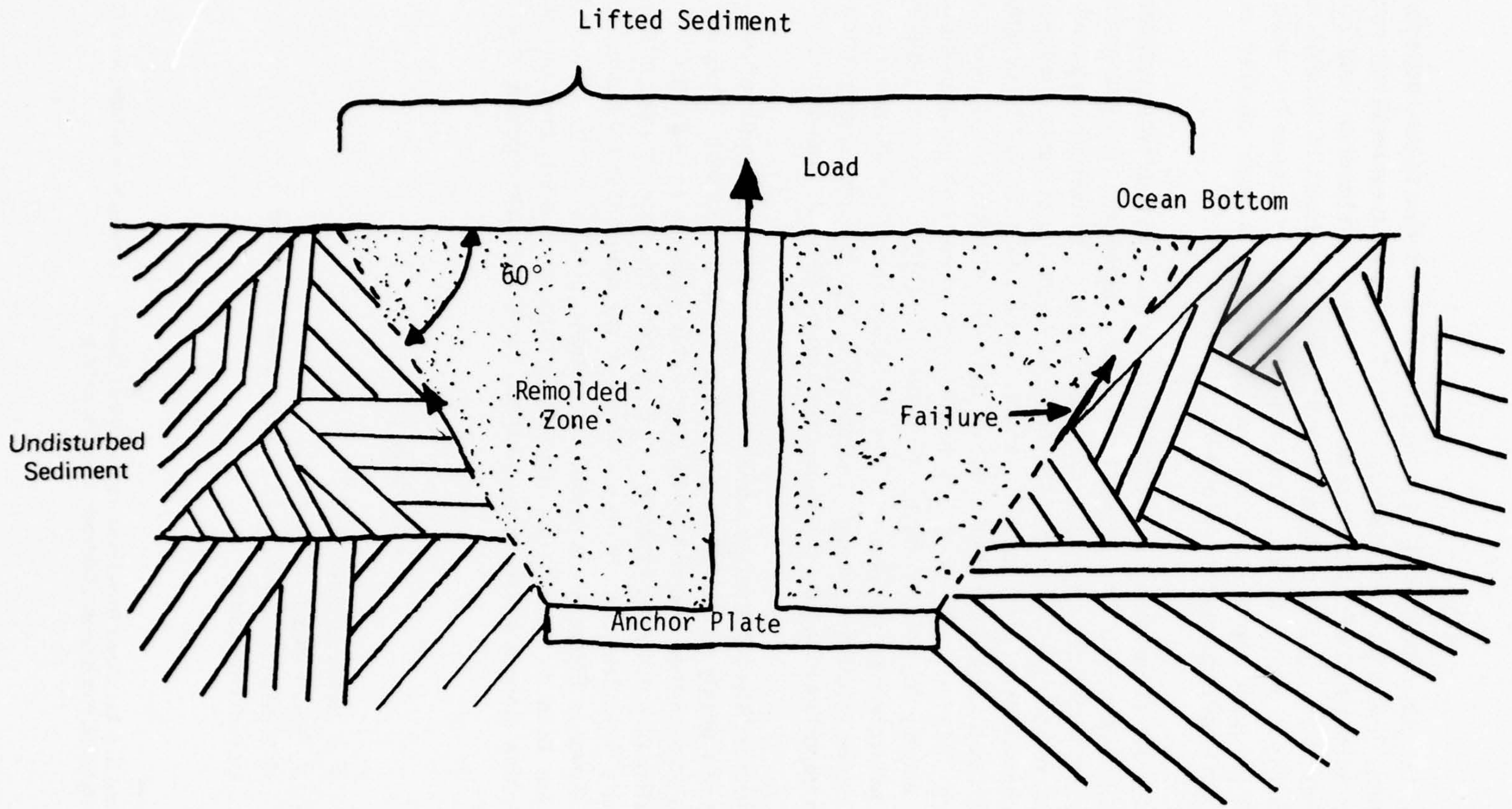


Figure 4. Failure by lifting a 30° sediment prism. (John A. Christians and Edward P. Meisburger, *Development of Multi-Leg Mooring System, Phase A – Explosive Embedment Anchor*, USAMERDC Report 1909A, Fort Belvoir, Virginia, December 1967, p. 276 [From Turner, July 1962].)

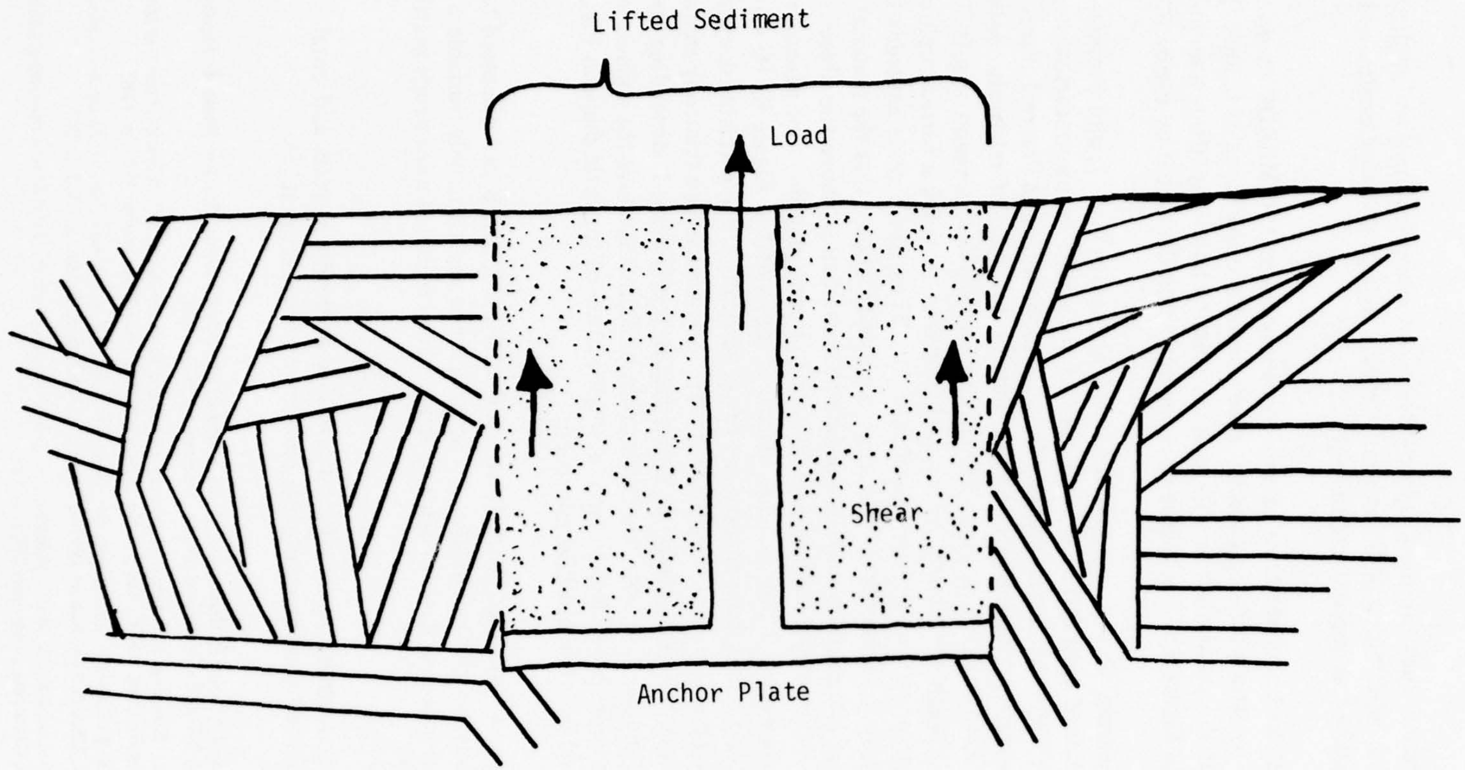


Figure 5. Vertical shearing surface. (John A. Christians and Edward P. Meisburger, *Development of Multi-Leg Mooring System, Phase A – Explosive Embedment Anchor*, USAMERDC Report 1909A, Fort Belvoir, Virginia, December 1967, p. 276 [After E. A. Turner, July 1962]).

"It should be noted that, in these approaches, conventional values are applied to both cohesive and cohesionless sediments with widely divergent characteristics so that they can be considered as approximations only.

"Model anchor plate tests have been conducted at USAMERDC to investigate the manner by which holding capacity is developed and the mode of failure. The data suggests that the anchor acquires its capacity prior to failure by lifting a sediment prism as shown in Figure 4 and at failure as in the condition illustrated by Figure 6."[29]

The shearing, or slip, surfaces illustrated in Figures 4, 5, 7, and 8 represent actual shapes obtained with different conditions of anchorage or are predicted shapes obtained through some theoretical means. The conditions shown in Figure 7, "according to Duke University experiments, occurs only in the case of relatively shallow anchors in dense sand or stiff silty clay. For shallow anchors in loose sand or soft clay, the slip surface, though not clearly established, is closer to being a vertical cylinder around the perimeter of the anchor (see Figure 5). Thus, for objects embedded in loose and compressible sediments, it is more reasonable to assume that the material involved in breakout is essentially only the sediment immediately above the object."[30] Vesic (1971) notes that very deeply buried anchors do not display the same general slip surface as shown in Figure 7 but, instead, behave as illustrated in Figure 8. He states that experiments show that deep anchors can travel vertically for appreciable distances by a failure mode similar to punching shear failure. After reaching a relatively shallow depth, these anchors behave as shown in either Figure 5 or Figure 7, depending upon the density of the sediment. Figure 4 shows a prism of sediment above the anchor, and this prism shape was probably derived from a simplification of the toric shape in Figure 7 or it was obtained by some intuitive approach.

10. Behavior of Coral and Rock Bottoms (Massive). Coral is not discussed to a great extent in any of the references. "The properties are extremely variable and depend on such things as organisms alive or dead, voids, included extraneous matter, fissures, and age."[31]

"Holding capacity cannot be estimated analytically in rock and coral. In these materials field tests and general experience must be relied upon."[32]

---

[29] John A. Christians and Edward P. Meisburger, *Development of Multi-Leg Mooring System: Phase A–Explosive Embedment Anchor,* USAMERDC Report 1909A, December 1967, p. 282.

[30] Aleksandar S. Vesic, "Breakout Resistance of Objects Embedded in Ocean Bottom," *Journal of the Soil Mechanics and Foundation Division,* ASCE, Vol. 97, No. SM9, Proc. Paper 8372, September 1971, p. 1187.

[31] John A. Christians and Edward P. Meisburger, *Development of Multi-Leg Mooring System: Phase A–Explosive Embedment Anchor,* USAMERDC Report 1909A, Fort Belvoir, Virginia, December 1967, p. 291.

[32] R. J. Taylor, D. Jones, and R. M. Beard, *Handbook of Lift-Resisting Anchors,* Naval Civil Engineering Laboratory, Port Hueneme, California, September 1975, p. 111.

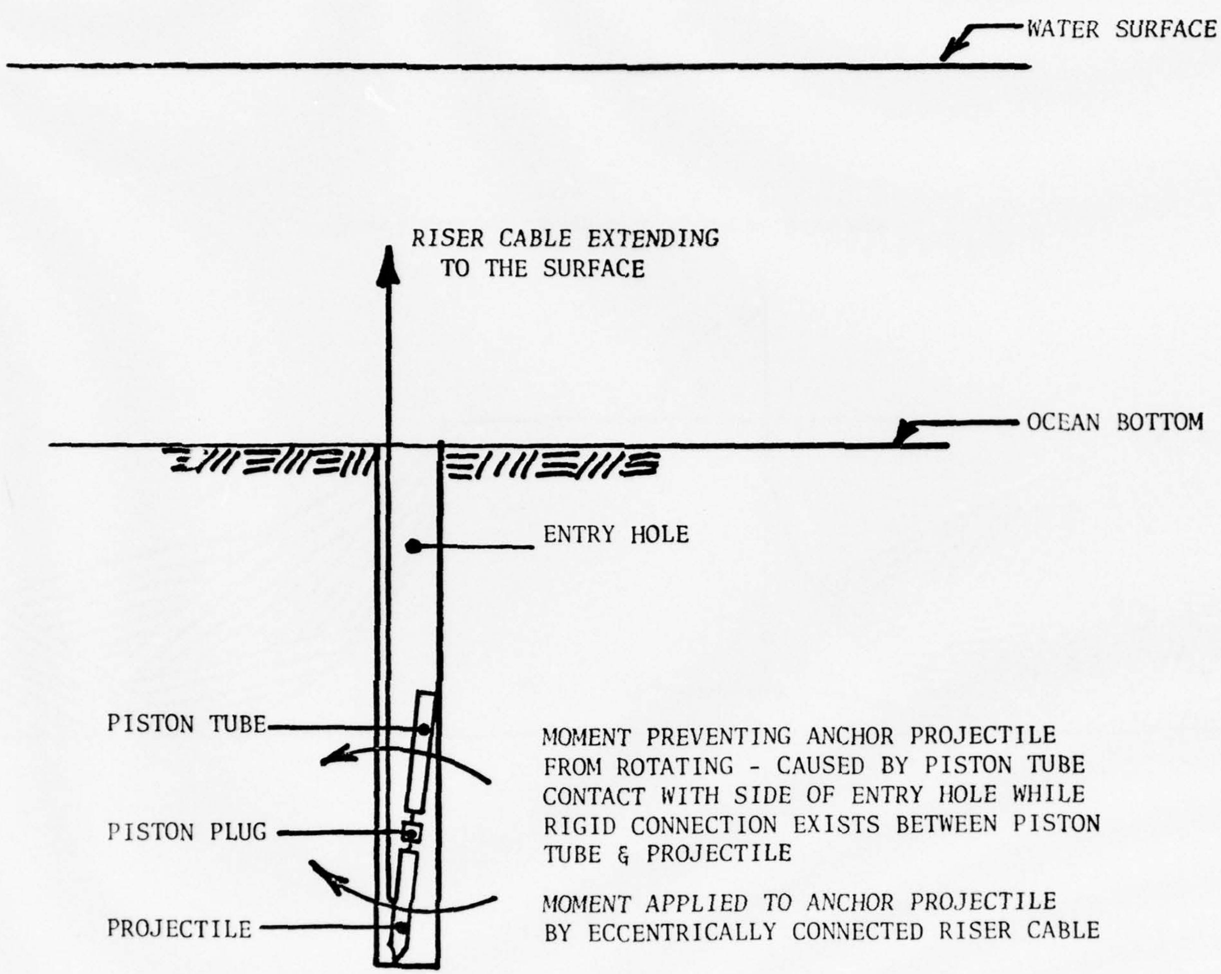


Figure 6. Embedment anchor keying failure.

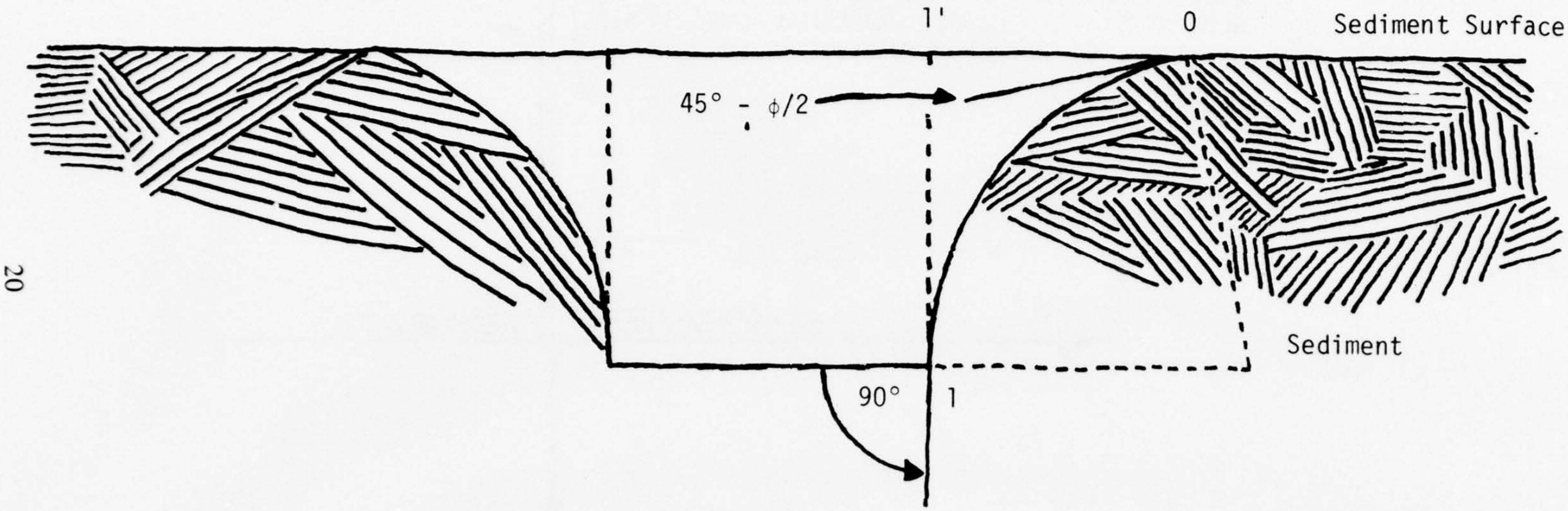


Figure 7. Shape of slip surface for circular buried objects.

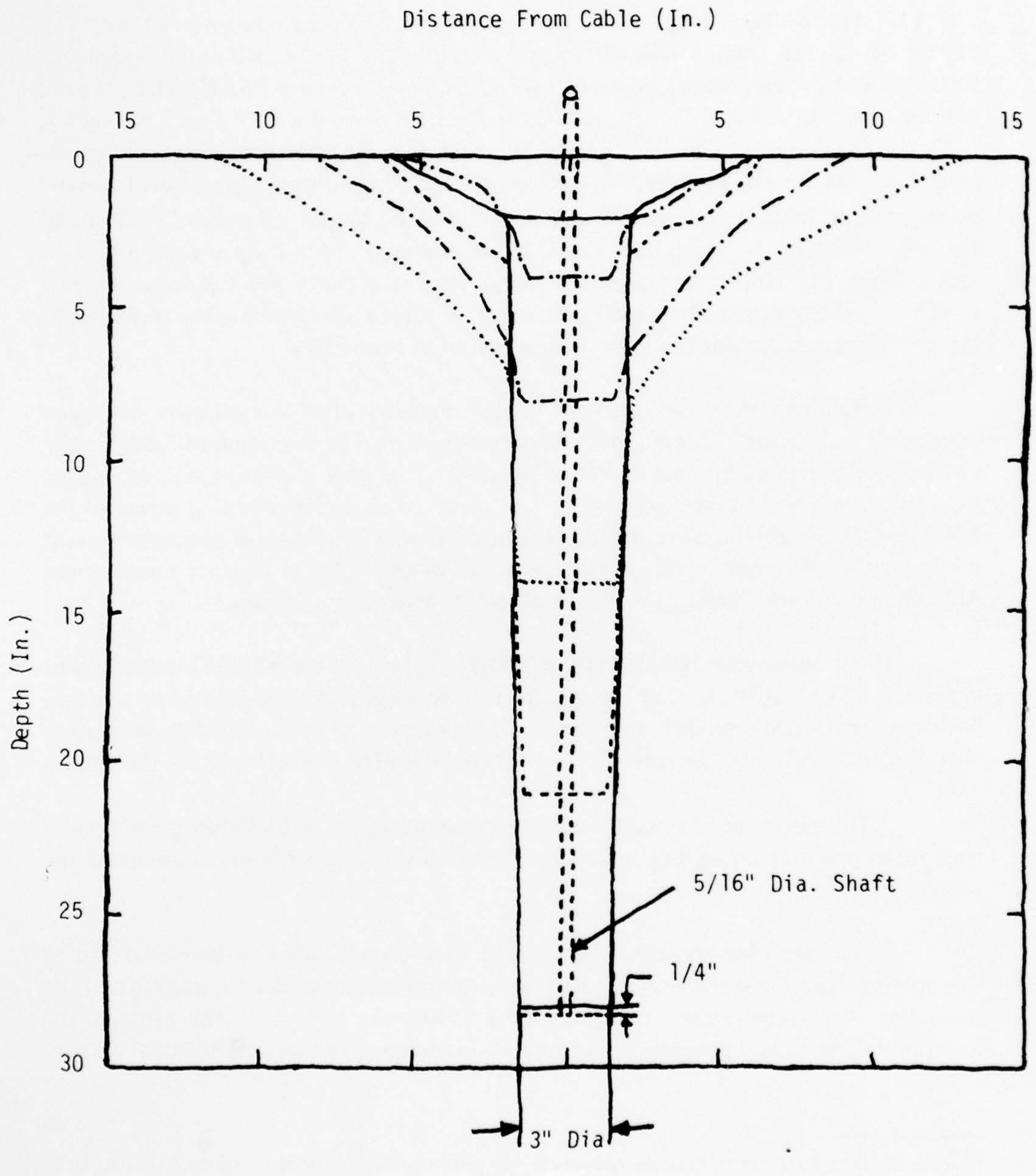


Figure 8. Observed shapes of slip surfaces caused by withdrawal of circular plates from stiff silty clay.

IV. PERFORMANCE OF THE XM-50 AND XM-200 EXPLOSIVE EMBEDMENT ANCHORS

11. Anchor Tests (MERADCOM, October 1962 through October 1972). The results of all the anchor tests performed by the U.S. Army Mobility Equipment Research and Development Command (MERADCOM) (formerly USAMERDC) for the present design of the XM-50 and XM-200 anchors are presented in Tables 2 through 5. Tables 2 and 3 summarize the tests of the anchors. Table 4 tabulates average performance data for the anchors. The creep data are derived for the most part from the same tests presented in Tables 2 and 3 as indicated in the "Test No." column of Table 4. Much of the creep data was obtained during proof-loading of the anchors, as indicated in the table. Creep data are also presented from two full-scale mooring tests.[33] The usefulness of this data, however, is somewhat questionable inasmuch as the mean of measurement was later determined to be imprecise.

Holding-power performance of the anchors after embedment has been reasonably satisfactory in terms of the design objectives. Examination of Table 5 indicates that the average holding power of the XM-50 anchors is above the design objectives for all sub-bottom compositions except mud. The average holding power of the XM-200 anchors, although not meeting the initial design objectives, is adequate in most sub-bottoms. However, a fairly wide variation in the holding capacity range of the XM-200 anchors was found to exist in most sub-bottom compositions.[34]

The apparent variability in the holding capacity of the XM-200 anchor can be explained in several ways. The major reason is believed to be the lack of precise sub-bottom data at the site of each installation. Even when excellent coring data were available, the anchors were frequently fired several hundred feet from the site of the core.

The existence of variable sub-bottom compositions within close proximity of each other (e.g., the sand/silt/clay/mud of the lower Chesapeake Bay) compounded the problem.[35]

Another phenomenon which could have been a factor in the variability of the holding capacity was the effect of the piston remaining at the trailing edge of the projectile after embedment. (See Figure 9.) This may have been the cause of the anchors' failing to key properly. A properly functioning explosive embedment anchor,

---

33 Henry C. Mayo, *Explosive Embedment Anchors For Ship Mooring*, USAMERDC Report 2078, November 1973, p. 25.

34 *Ibid.*, p. 31.

35 *Ibid.*, p. 31.

Table 2. Summary of XM-50 Anchor Tests

Test No.	Location	Date Installed	Sub-Bottom Composition	Water Depth (ft (m))	Propellant Weight (lb (kg))	Penetration (ft (m))	Ultimate Holding Capacity (lb (kg))	Remarks
1	Potomac River, Va-Md	9 Oct 62	Mud over sand	26 (7.9)	3 (1.36)	None	None	Anchor malfunctioned
2	Potomac River, Va-Md	9 Oct 62	Mud over sand	26 (7.9)	3 (1.36)	24 (7.3)	72,000 (32,659)	
3	Key West, Fla	21 May 63	Coral	40 (12.2)	3 (1.36)	17 (5.2)	65,000 (29,484)	
4	Key West, Fla	22 May 63	Coral	42 (12.8)	3 (1.36)	22 (6.7)	80,000 (36,288)	
5	Chesapeake Bay, Norfolk, Va	25 Jul 63	Clay	47 (14.3)	3.5 (1.58)	25 (7.6)	100,000 (45,360 combined	Pulled in parallel with No. 6
6	Chesapeake Bay, Norfolk, Va	25 Jul 63	Clay	47 (14.3)	3 (1.36)	23 (7.0)		Pulled in parallel with No. 5
7	Chesapeake Bay, Norfolk, Va	26 Jul 63	Clay	45 (13.7)	3.5 (1.58)	25 (7.6)	60,000 (27,216)	Riser cable failed
8	Chesapeake Bay, Norfolk, Va	29 Jul 63	Sand	45 (13.7)	3 (1.36)	19 (5.8)	75,000 (34,020)	Riser cable failed
9	Chesapeake Bay, Norfolk, Va	30 Jul 63	Sand	45 (13.7)	3.5 (1.58)	23 (7.0)	112,000 (50,803) combined	Pulled in parallel with No. 10; riser cable failed
10	Chesapeake Bay, Norfolk, Va	30 Jul 63	Sand	45 (13.7)	3.5 (1.58)	26 (7.9)		Pulled in parallel with No. 9; riser cable failed
11	Chesapeake Bay, Norfolk, Va	8 Oct 64	Clay	43 (13.1)	3.5 (1.58)	22 (6.7	105,000 (47,628) combined	Pulled in parallel with No. 12; riser cable failed
12	Chesapeake Bay, Norfolk, Va	8 Oct 64	Clay	43 (13.1)	3.5 (1.58)	22 (6.7)		Pulled in parallel with No. 11; riser cable failed
13	Potomac River, Va-Md	64	Mud	51 (15.5)	3.5 (1.58)	41 (12.5)	15,000 (6,804)	
14	Potomac River, Va-Md	24 Oct 69	Mud/clay	25 (7.6)	3.5 (1.58)	21 (6.4)	None	Fuze used; riser cable failed

Table 2. Summary of XM-50 Anchor Tests (Cont'd)

Test No.	Location	Date Installed	Sub-Bottom Composition	Water Depth (ft (m))	Propellant Weight (lb (kg))	Penetration (ft (m))	Ultimate Holding Capacity (lb (kg))	Remarks
15	Potomac River, Va-Md	24 Nov 69	Sand/gravel	25 (7.6)	3.5 (1.58)	16 (4.9)	70,000 (31,752)	Fuze and pendant used; thimble failed;
16	Chesapeake Bay, Fort Story, Va	24 Aug 72	Sand/silt/clay/mud	45 (13.7) approx	3.5 (1.58)	40 (12.2)	45,000 (20,412)	Fuze and pendant used; pendant failed;
17	Atlantic Ocean, Fort Story, Va	15 Sep 72	Sand	9 (2.7)	3.5 (1.58)	13 (4.0)	NA	Firing stand malfunctioned; anchor not pulled
18	Atlantic Ocean, Fort Story, Va	15 Sep 72	Sand	10 (3.0)	3.5 (1.58)	16 (4.9)	NA	Firing Stand malfunctioned; holding capacity not measured

Table 3. Summary of XM-200 Anchor Tests

Test No.	Location	Date Installed	Sub-Bottom Composition	Water Depth (ft (kg))	Propellant Weight (lb (kg))	Penetration (ft (m))	Ultimate Holding Capacity (lb (kg))	Remarks
1	Key West, Fla	7 Mar 63	Coral	45 (13.7)	14 (6.35)	17 (5.2)	145,000 (65,772)	Keying flap failure
2	Key West, Fla	6 May 63	Coral	46 (14.0)	12 (5.44)	18 (5.5)	60,000 (27,216)	Keying flap failure
3	Key West, Fla	10 May 63	Coral	47 (14.3)	14 (6.35)	19 (5.8)	100,000 (45,360)	Keying flap failure
4	Key West, Fla	13 May 63	Coral	46 (14.0)	13 (5.90)	21 (6.4)	215,000 (97,523)	Keying flap failure
5	Key West, Fla	16 May 63	Mud/coral	38 (11.6)	12 (5.44)	28 (8.5)	115,000 (52,164)	Keying flap failure
6	Key West Fla	17 May 63	Mud/coral	39 (11.9)	14 (6.35)	31 (9.4)	125,000 (56,700)	Keying flap failure
7	Key West, Fla	23 May 63	Coral	45 (13.7)	13 (5.90)	10 (3.0)	220,000 (99,791)	
8	Chesapeake Bay, Norfolk, Va	1 Aug 63	Sand	46 (14.0)	12 (5.44)	24 (7.3)	140,000 (63,504)	Keying flap failure
9	Chesapeake Bay, Norfolk Va	7 Aug 63	Sand	43 (13.1)	14 (6.35)	30 (9.1)	282,000 (127,914)	Riser cable failure
10	Chesapeake Bay, Norfolk, Va	12 Aug 63	Sand	45 (13.7)	13 (5.90)	21 (6.4)	220,000 (99,791)	
11	Chesapeake Bay, Norfolk, Va	15 Aug 63	Sand	41 (12.5)	14 (6.35)	20 (6.1)	245,000 (111,131)	Riser cable failure
12	Chesapeake Bay, Norfolk, Va	19 Aug 63	Sand	44 (13.4)	14 (6.35)	28 (8.5)	77,000 (34,927)	Riser cable failure; flaps not used
13	Chesapeake Bay, Norfolk, Va	20 Aug 63	Clay	43 (13.1)	13 (5.90)	25 (7.6)	150,000 (68,040)	Keying flap failure
14	Potomac River, Va-Md	16 Apr 64	Clay/mud	51 (15.5)	14 (6.35)	16 (4.9)	75,000 (34,020)	
15	Potomac River, Va-Md	15 Jul 64	Clay/mud	49 (14.9)	14 (6.35)	22 (6.7)	53,000 (24,041	Keying flap failure
16	Potomac River, Va-Md	24 Jul 64	Clay/mud	52 (15.8)	14 (6.35)	14 (4.3)	60,000 (27,216)	
17	Potomac River, Va-Md	29 Jul 64	Silt/mud	54 (16.5)	14 (6.35)	26 (7.9)	70,000 (31,752)	

Table 3. Summary of XM-200 Anchor Tests (Cont'd)

Test No.	Location	Date Installed	Sub-Bottom Composition	Water Depth (ft (kg))	Propellant Weight (lb (kg))	Penetration (ft (m))	Ultimate Holding Capacity (lb (kg))	Remarks
18	Potomac River, Va-Md	11 Aug 64	Mud	55 (16.8)	14 (6.35)	33 (10.1)	44,000 (19,958)	
19	Potomac River, Va-Md	13 Aug 64	Mud	55 (16.8)	14 (6.35)	42 (12.8)	60,000 (27,216)	
20	Chesapeake Bay, Norfolk, Va	26 Oct 64	Clay	40 (12.2)	14 (6.35)	22 (6.7)	250,000 (113,399)	
21	Chesapeake Bay, Norfolk, Va	27 Oct 64	Clay	40 (12.2)	14 (6.35)	19 (5.8)	180,000 (81,647)	Anchor projectile broke (casting)
22	Chesapeake Bay, Norfolk, Va	28 Oct 64	Sand	43 (13.1)	14 (6.35)	21 (6.4)	190,000 (86,183)	Riser cable failure
23	Chesapeake Bay, Norfolk, Va	2 Nov 64	Sand	41 (12.5)	14 (6.35)	20 (6.1)	180,000 (81,647)	
24	Chesapeake Bay, Norfolk, Va	4 Nov 64	Silt	46 (14.0)	14 (6.35)	–	–	Anchor not vertical when fired
25	Chesapeake Bay, Norfolk, Va	5 Nov 64	Silt	46 (14.0)	14 (6.35)	24 (7.3)	180,000 (81,647)	
26	Chesapeake Bay, Fort Story, Va	Apr 66	Sand/silt/clay/mud	50 (15.2)	14 (6.35)	49 (14.9)	80,000 (36,288)	Fuze used
27	Chesapeake Bay, Fort Story, Va	17 Aug 66	Sand/silt/clay/mud	42 (13.1)	14 (6.35)	38 (11.6)	53,000 (24,041)	Fuze used
28	Chesapeake Bay, Fort Story, Va	17 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	36 (11.0)	100,000 (45,360)	Fuze used
29	Chesapeake Bay, Fort Story, Va	17 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	28 (8.5)	120,000 (54,432)	Fuze used; keying flap malfunctioned
30	Chesapeake Bay, Fort Story, Va	22 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	40 (12.2)	36,000 (16,329)	Fuze used
31	Chesapeake Bay, Fort Story, Va	22 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	35 (10.6)	195,000 (88,451)	Fuze used

Table 3. Summary of XM-200 Anchor Tests (Cont'd)

Test No.	Location	Date Installed	Sub-Bottom Composition	Water Depth (ft (kg))	Propellant Weight (lb (kg))	Penetration (ft (m))	Ultimate Holding Capacity (lb (kg))	Remarks
32	Chesapeake Bay, Fort Story, Va	24 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	19 (5.8)	50,000 (22,680)	Fuze used
33	Chesapeake Bay, Fort Story, Va	25 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	36 (11.0)	70,000 (31,751)	Riser cable damaged; fuze used; keying flap malfunctioned
34	Chesapeake Bay, Fort Story, Va	25 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	24 (7.3)	110,000 (49,896)	Fuze used
35	Chesapeake Bay, Fort Story, Va	29 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	38 (11.6)	40,000 (18,144)	Fuze used; keying flap malfunctioned
36	Chesapeake Bay, Fort Story, Va	30 Sep 66	Sand/silt/clay/mud	43 (13.1)	14 (6.35)	16 (4.9)	105,000 (47,628)	Fuze used; keying flap malfunctioned
37	Potomac River, Va-Md	14 Feb 68	Mud	45 (13.7) approx	14 (6.35)	36 (11.0)	50,000 (22,680)	Fuze used; projectile broken (casting)
38	Potomac River, Va-Md	18 Mar 70	Mud	51 (15.5)	14 (6.35)	41 (12.5)	30,000 (13,608)	Fuze used; nylon
39	Atlantic Ocean, Fort Story, Va	22 Sep 72	Sand over mud	36 (11.0)	14 (6.35)	42 (12.8)	130,000 (58,968)	Fuze used; pulling gear failed
40	Atlantic Ocean, Fort Story, Va	25 Sep 72	Sand over mud	36 (11.0)	14 (6.35)	44 (13.4)	118,000 (53,524)	Fuze used; pulling gear failed
41	Atlantic Ocean, Fort Story, Va	26 Sep 72	Sand over mud	40 (12.2)	14 (6.35)	39 (11.9)	85,000 (38,556)	Fuze used
42	Atlantic Ocean, Fort Story, Va	29 Sep 72	Sand over mud	46 (14.0)	14 (6.35)	32 (9.8)	70,000 (31,752)	Fuze used

Table 4. Short-Term Creep of EEA's

Test No.	Date	Type Anchor	Initial Penetration (ft (m))	Sub-Bottom Composition	Loading Method	Load Range (kip (metric ton))	Load Duration	Creep (ft (m))	Remarks
A	Jan-Feb 64	XM-200	21 (6.4)	Clay	Barge-constant/cyclic	0-200 (0-90.7)	52.2 h	1/3 (0.1)	Anchor pile driven in to sub-bottom
B	Feb 64	XM-200	20-2/3 (6.3)	Clay	Barge-constant	100-201 (45.3-91.1)	13 h	4 (1.2)	Same anchor as test A
C	Feb 64	XM-200	16-1/2 (5.0)	Clay	Barge-constant	100 (45.3) max	10 min	16-1/2 (5.0)	Same anchor as test B; keying flap failure
28	3-6 Oct 66	XM-200	36 (11.0)	Sand/silt/clay	T-5 tanker	Approx 49 (22.2) max	70 h	0	
28A	12 Oct 66	XM-200	36 (11.0)	Sand/silt/clay	Barge-constant	100 (45.3) max	Approx 30 min	36 (11.0)	Pullout loading
29	27 Sep 66	XM-200	28 (8.5)	Sand/silt/clay	Barge-constant	0-100 (0-45.3)	Approx 5 min	4 (1.2)	Proof loading
29A	3-6 Oct 66	XM-200	24 (7.3)	Sand/silt/clay	T-5 tanker	Approx 11 (4.98) max	70 h	3 (0.9)	
29B	12 Oct 66	XM-200	21 (6.4)	Sand/silt/clay	Barge-constant	120 (54.4) max	Approx 17 min	21 (6.4)	Pullout loading
30	27 Sep 66	XM-200	40 (12.2)	Sand/silt/clay	Barge-constant	0-36 (0-16.3)	Approx 15 min	15 (4.6)	Proof loading
30A	28 Sep 66	XM-200	25 (7.6)	Sand/silt/clay	Barge-constant	0-30 (0-13.6)	Approx 10 min	14 (4.3)	Proof loading
31	28 Sep 66	XM-200	35 (10.6)	Sand/silt/clay	Barge-constant	0-75 (0-34.0)	Approx 15 min	15 (4.6)	Proof loading
32	27 Sep 66	XM-200	19 (5.8)	Sand/silt/clay	Barge-constant	0-50 (0-22.6)	Approx 10 min	9 (2.7)	Proof loading
32A	3-6 Oct 66	XM-200	10 (3.0)	Sand/silt/clay	T-5 tanker	Approx 20 (9.0) max	See Remarks	10 (3.0)	Load duration less than 70 h; bridled to anchor 36A

Table 4. Short-Term Creep of EEA's (Cont'd)

Test No.	Date	Type Anchor	Initial Penetration (ft (m))	Sub-Bottom Composition	Loading Method	Load Range (kip (metric ton))	Load Duration	Creep (ft (m))	Remarks
33	3-6 Oct 66	XM-200	36 (11.0)	Sand/silt/clay	T-5 tanker	Negligible	70 h	0	
33A	7 Oct 66	XM-200	36 (11.0)	Sand/silt/clay	Barge-constant	70 (31.7) max	Approx 29 min	36 (11.0)	Pullout loading
34	3-6 Oct 66	XM-200	24 (7.3)	Sand/silt/clay	T-5 tanker	Approx 4 (1.8) max	46 h	0	
34A	7 Oct 66	XM-200	24 (7.3)	Sand/silt/clay	Barge-constant	110 (49.9) max	Approx 19 min	24 (7.3)	Pullout loading
35	29 Sep 66	XM-200	38 (11.6)	Sand/silt/clay	Barge-constant	0-30 (0-13.6)	Approx 10 min	10 (3.0)	Proof loading
35A	3-6 Oct 66	XM-200	28 (8.5)	Sand/silt/clay	T-5 tanker	Approx 29 (13.1) max	70 h	0	Bridled to anchor 30 during this test
35B	11 Oct 66	XM-200	28 (8.5)	Sand/silt/clay	Barge-constant	40 (18.1) max	Approx 22 min	28 (8.5)	Pullout loading
36	30 Sep 66	XM-200	16 (4.9)	Sand/silt/clay	Barge-constant	0-35 (0-15.9)	Approx 5 min	4 (1.2)	Proof loading
36A	3-6 Oct 66	XM-200	12 (3.7)	Sand/silt/clay	T-5 tanker	Approx 48 (21.8) max	70 h	4 (1.2)	Bridled to anchor 32A
36B	12 Oct 66	XM-200	8 (2.4)	Sand/silt/clay	Barge-constant	105 (47.6) max	Approx 6 min	8 (2.4)	Pullout loading
39	22 Sep 72	XM-200	42 (12.8)	Sand over mud	Barge constant	0-40 (0-18.1)	Approx 17 min	17 (5.2)	Proof loading
39A	11-13 Oct 72	XM-200	25 (7.6)	Sand over mud	LST ship	1-approx 100 (45.3)	36 h 51 min	6 (1.8)	
39B	26 Oct 72	XM-200	19 (5.8)	Sand over mud	Barge-constant	19-90 (8.6-40.8)	7 min	6 (1.8)	
39C	26 Oct 72	XM-200	13 (4.0)	Sand over mud	Barge-constant	45-130 (20.4-59.0)	8 min	Approx 1 (0.3)	

Table 4. Short-Term Creep of EEA's (Cont'd)

Test No.	Date	Type Anchor	Initial Penetration (ft (m))	Sub-Bottom Composition	Loading Method	Load Range (kip (metric ton))	Load Duration	Creep (ft (m))	Remarks
40	25 Sep 72	XM-200	44 (13.4)	Sand over mud	Barge-constant	–	Approx 10 min	10 (3.0)	Installed 30-40 feet (9.1-12.2 m) from anchor 39; proof loading
40A	11-13 Oct 72	XM-200	34 (10.4)	Sand over mud	LST ship	1-approx 100 (45.3)	36 h 51 min	9 (2.7)	
40B	26 Oct 72	XM-200	25 (7.6)	Sand over mud	Barge-constant	5-100 (2.3-45.3)	27 min	12 (3.7)	
40C	26 Oct 72	XM-200	13 (4.0)	Sand over mud	Barge-constant	10-118 (4.5-54.0)	42 min	Approx 2 (0.6)	
41	26 Sep 72	XM-200	39 (11.9)	Sand over mud	Barge-constant		Approx 7 min	7 (2.1)	Proof loading
41A	24 Oct 72	XM-200	32 (9.8)	Sand over mud	Barge-constant	10-85 (4.5-38.6)	35 min	26 (7.9)	
41B	24 Oct 72	XM-200	6 (1.8)	Sand over mud	Barge-constant	58 (26.3) max	4 min	6 (1.8)	Pullout loading
42	29 Sep 72	XM-200	32 (9.8)	Sand over mud	Barge constant	0-26 (0-11.8)	5 min	8 (2.4)	Proof loading
42A	24 Oct 72	XM-200	24 (7.3)	Sand over mud	Barge-constant	70 (31.7) max	7 min	24 (7.3)	Pullout loading
15	Nov 69	XM-50	16 (4.9)	Sand/gravel	Barge-constant	0-59 (26.8)	20 min	Approx 1 (0.3)	
15A	Nov 69	XM-50	15 (4.6)	Sand/gravel	Barge-constant	53 (24.0) steady	4 h	0	Clamp-thimble failed at 70,000-lb (31,800-kg) loading

Table 5. Average Penetration and Holding Capacity of EEA's

Type Anchor	Number of Tests	Sub-Bottom Composition	Average Penetration (ft (m))	Average Ultimate Holding Capacity (kip (metric ton))	Holding Capacity Range (kip (metric ton))
XM-200	3	Clay	22 (6.7)	193 (87.5)	150-250 (68.0-113.4)
XM-200	7	Sand	23 (7.0)	191 (86.6)	77-282 (34.9-127.9)
XM-200	1	Silt	24 (7.3)	180 (81.6)	NA
XM-200	5	Coral	17 (5.2)	148 (67.1)	60-220 (27.2-99.8)
XM-200	2	Mud/coral	30 (9.1)	120 (54.4)	115-125 (52.2-56.7)
XM-200	4	Sand over mud	39 (11.9)	101 (45.8)	70-130 (31.8-59.0)
XM-200	11	Sand/silt/clay/mud	33 (10.1)	87 (39.4)	36-195 (16.3-88.5)
XM-200	1	Silt/mud	26 (7.9)	70 (31.7)	NA
XM-200	3	Clay/mud	17 (5.2)	63 (28.6)	53-75 (24.0-34.0)
XM-200	4	Mud	38 (11.6)	46 (20.9)	30-60 (13.6-27.2)
XM-50	2	Coral	20 (6.1)	72 (32.7)	65-80 (29.5-36.3)
XM-50	1	Mud over sand	24 (7.3)	72 (32.7)	NA
XM-50	1	Sand/gravel	16 (4.9)	70 (31.7)	NA
XM-50	3	Sand	23 (7.0)	62 (28.1)	56-75 (25.4-34.0)
XM-50	5	Clay	23 (7.0)	53 (24.0)	50-60 (22.7-27.2)
XM-50	1	Sand/silt/clay/mud	40 (12.2)	45 (20.4)	NA
XM-50	1	Mud	41 (12.5)	15 (6.8)	NA

after penetrating the ocean bottom and coming to rest within the sub-bottom sediments, will key upon a load being applied. An anchor keys when it turns in the sediment to a position that is perpendicular to the axis of the applied load.

Examining the problem more closely, it should be noted that both conventional and unconventional anchors perform somewhat erratically, i.e., the extraction forces developed by identical anchors positioned in identical bottom materials, and loaded identically, yield extraction force data which tend to be widely scattered. Given this, failure of a single mooring anchor could be attributed to an isolated, abnormally low resistance to extraction even in the presence of three other anchors whose performance was at least adequate.[36]

Another factor which may affect the holding capacity of the anchors is the amount of time required for the sub-bottom sediment to partially stabilize after being disturbed during penetration by the anchor projectile. This is particularly important when the anchor is pulled vertically through the disturbed sediment immediately after penetration. It is felt that greater holding capacity can be obtained either by waiting a period of time (the longer the better) before loading the anchor or by loading the anchor at a 45° angle or greater from the vertical so that the anchor is pulled through

[36] Frank Cevasco, *EPR Correction Summary, Multi-Leg Tanker Mooring System and Unloading Facility*, (DT-II) July 1975.

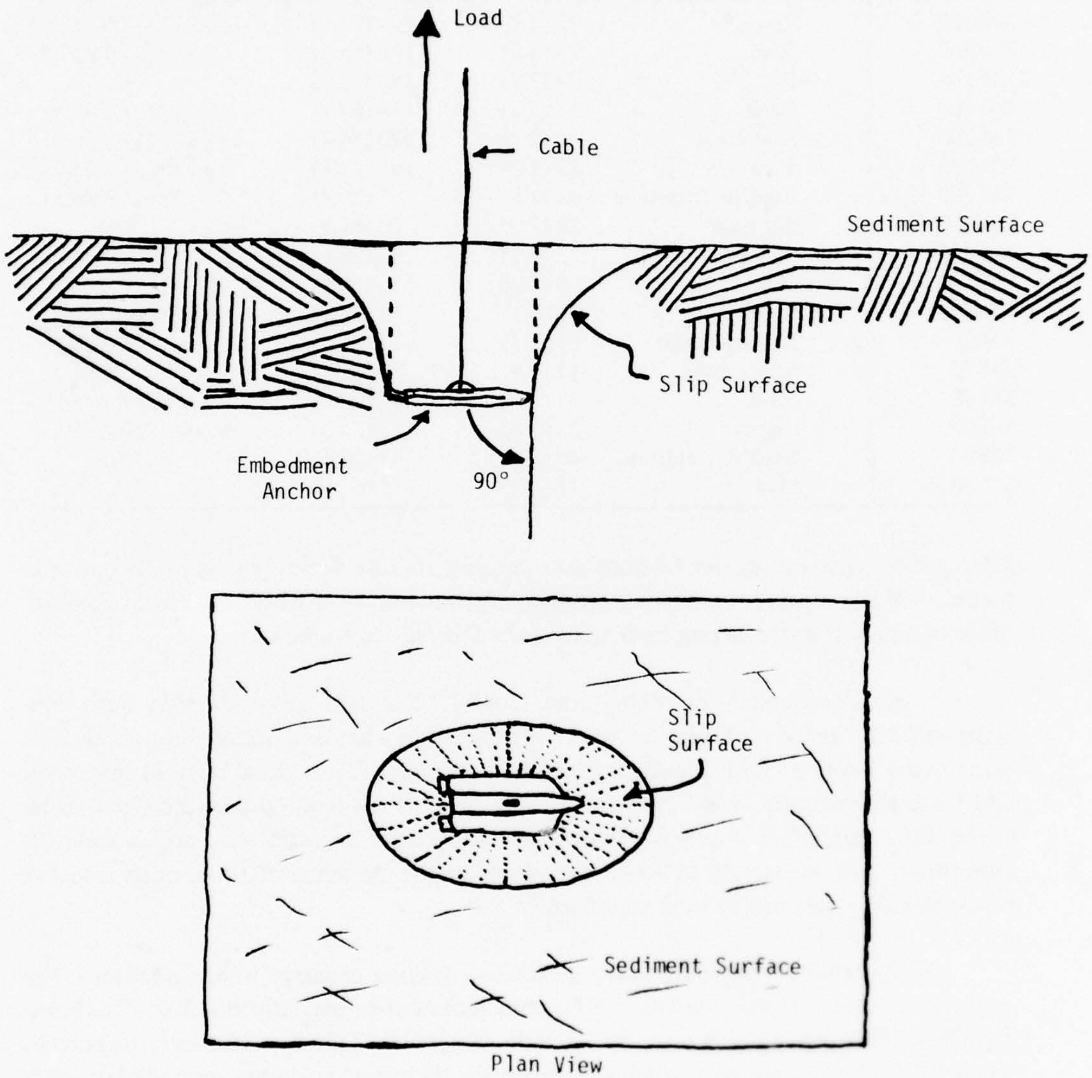


Figure 9. Possible shape of the slip surface for EEA's.

undisturbed sediment. It should be noted that, except for the unstable sediment phenomenon, it is not generally expected that the angle of pull will have much effect on the holding power of the anchor. The exception to this is the case where the anchor penetration is low in a stiff (e.g., gravel) sub-bottom, when a nonvertical pull will probably produce greater capacity.[37]

Since embedment anchors generally do not tend to achieve greater penetration when a load is applied, the vertical creep rate of the anchor under load is an important factor. Tables 2 and 3 cover the efforts made by the Army investigations on the creep of the XM-50 and XM-200 anchors.[38]

12. **Anchor Tests (Materiel Testing Directorate, APG, and the U.S. Army Armor and Engineering Board).** The DT-II (Engineering Phase) was conducted by the Materiel Testing Directorate, Aberdeen Proving Ground (APG), between February 1974 and June 1975. Conduct of the DT-II (Service-Use Phase) testing was by the U.S. Army Armor and Engineering Board during May and June 1974. The tests were conducted at three test sites having different ocean bottom conditions. These sites, and the corresponding bottom conditions, were:

a. Camp LeJuene, North Carolina: sand and clay bottom
b. Eglin AFB, Florida: sand bottom
c. Fort Story, Virginia: layered silt, sand, and clay bottom[39]

The extraction forces and depths of penetration of the individual EEA's are presented in Table 6. The mean and standard deviation of these data for each bottom condition tested are presented in Table 7.

Because the extraction forces for the EEA's deployed at the Eglin AFB test site were below 50,000 pounds (222,410 N), a close examination of the failure of the piston plugs to separate from the anchors was conducted. This examination established that, as a result of this condition, the anchors failed to key properly as they penetrated the ocean bottom. The development of maximum holding forces is directly dependent upon proper keying of the anchor. A modified (shorter) piston plug was developed. Although the modified plug was not available in time to be utilized at the Eglin AFB test site, the modified plug was used during the second test exercise conducted at Camp LeJuene. At that time, five anchors employing the shorter plugs and five anchors with the longer plugs were developed. A comparison of the performance

[37] Henry C. Mayo, *Explosive Embedment Anchors For Ship Mooring*, USAMERDC Report 2078, November 1973.

[38] *Ibid.*

[39] Gary M. Jastrab, *Development Test II (Engineering Phase) of Multi-Leg Tanker Mooring System, Final Report*, Report AGP-MT-4695, U.S. Army TECOM, Aberdeen Proving Ground, Maryland, August 1975, p. 14.

Table 6. XM-50 Anchor Tests (DT-II)

Test Site	EEA Number	Extraction Force (lb (kg))	Penetration (ft (m))	Sediment Type
Camp LeJuene	1	100,000 (45,359.7)	12 (3.66)	Stiff Clay
	2	62,700 (28,440.5)	11.75 (3.58)	
	3	100,000 (45,359.7)	13.17 (4.01)	
	4	34,000 (15,422.3)	15.25 (4.65)	Stiff Sand/Clay
	5	97,200 (44,089.6)	12 (3.66)	
	6	71,000 (32,205.4)	12 (3.66)	
	7	95,000 (43,091.7)	15.33 (4.67)	Stiff Clay
	8	70,000 (31,751.8)	15 (4.57)	
	9	64,000 (29,030.2)	14 (4.27)	
	10	71,000 (32,205.4)	15.25 (4.65)	
Eglin AFB	1	31,900 (14,469.7)	10 (3.05)	
	2	32,900 (14,923.3)	14.25 (4.34)	
	3	39,600 (17,962.4)	12 (3.66)	
	4	33,100 (15,014.1)	12 (3.66)	
	5	30,400 (13,789.3)	12 (3.66)	
	6	23,500 (10,659.5)	10 (3.05)	Stiff Sand/Clay
	7	24,000 (10,886.3)	12 (3.66)	
	8	30,500 (13,834.7)	17 (5.18)	
	9	45,400 (20,593.3)	NA	
	10	31,500 (14,288.3)	NA	
Fort Story	1	24,500 (11,113.1)	24 (7.32)	
	2	31,000 (14,061.5)	23 (7.01)	
	3	35,500 (16,102.7)	21 (6.40)	
	4	28,000 (12,700.7)	NA	
	5	32,000 (14,515.1)	NA	

Test Dates: 19 February 1974 through 12 June 1975.

of these anchors established that in every instance in which the short plug was used the piston plug separated from the anchor; the anchors incorporating the short piston plugs developed greater holding forces than the anchors fired with the original (long) plug; consequently, the short piston plugs were designated as the proper plugs for the EEA's.[40] The mean holding force for EEA's using the short plug was 78,784 pounds (35,736.1 kilograms), while the figure for the long plug was 74,200 pounds (33,656.9 kilograms).[41]

---

40 *Ibid.*, pp. 65-66.

41 *Ibid.*, p. 85.

Table 7. Mean and Standard Deviation of Extraction Forces and Penetration of EEA's

Location and Bottom Condition	Mean Extraction Force (lb (kg))	Standard Direction of Extraction Force (lb (kg))	Mean Penetration (ft (m))	Standard Direction of Penetration (ft (m))
Camp LeJuene (Stiff Clay)	97,500 (44,225.7)[a]	3,535 (1,603.5)[a]	13.67 (4.17)[a]	2.35 (0.72)[a]
Camp LeJuene (Stiff Sand and Clay)	71,240 (32,314.3)[b]	20,800 (9,434.8)[b]	23.55 (4.13)[b]	1.52 (0.46)[b]
Eglin AFB (Sand)	32,230 (14,619.4)	6,400 (2,903.0)	12.41 (3.78)	2.29 (0.70)
Fort Story (Silt, Sand, and Clay)	20,750 (9,412.1)	4,600 (2,086.5)	22.67 (6.90)	1.53 (0.47)

(a) Calculated by averaging 2 values measured previously.

(b) Calculated from data for both long and short piston plugs.

13. **Performance in General.** The design configuration of the Army anchors, which are mechanically simple with low projectile means and frontal area, has proved successful overall. The use of a single projectile for all bottom conditions is convenient and reliable operationally but results in seriously reduced holding capacity in softer sub-bottoms. The impact of the reduced capability may be overcome by careful application of proof-loading procedures and by bridling two anchors when necessary.[42]

In general, the tests " . . . indicate that the Army explosive embedment anchors meet the Army's performance objectives for ship mooring, unless mud or other soft sediments with low shear strength are encountered. The EEA's were not designed for use in massive rock sea floors. There has, however, been good performance obtained in coral bottoms."[43]

42 Henry C. Mayo, *Explosive Embedment Anchors For Ship Mooring*, USAMERDC Report 2078, November 1973, p. 33.

43 *Ibid.*

V. CONCLUSIONS

14. Conclusions. Because of the very high variability of possible sediment types that can be encountered in ocean bottoms, it is both reasonable and suitable to ". . . subdivide the problem of predicting embedment anchor holding capacities into several areas. The same anchor may produce significantly different capacities under different loading and sediment conditions."[44]

In this report, the main concern was given to long-term repeated load conditions in both cohesive and cohesionless sediments. Due to the shortage of research and study in this area "it is necessary to combine work from other areas with the small amount of directly applicable research to yield approximate, immediately usable results."[45]

A suggested prediction procedure for determining extraction forces is given by Taylor and Lee.[46] This procedure is not the answer to all problems but may serve as a "best guess" until more study and research are done in the area of predicting extraction forces. Another suggested prediction was referred to earlier in this report for the prediction of penetration forces.

The analysis presented in section III and in the appendix of this report reveals the very complex nature of the phenomena involved in breakout of objects embedded in the ocean bottom. It should be obvious that no single equation, no matter how elaborate, could be fully satisfactory for *all* varieties of sediment condition as well as for methods of placement and types of objects to be extracted.

Based on the Duke University tests mentioned earlier in this presentation, it can be hypothesized that the shape of the slip surface for explosive embedment anchors would probably be as shown in Figure 9. This figure is a modification of Figure 10 (appendix), showing the slip surfaces not only from a side view but also from a plan (overhead) view. No tests have been performed which could be used to prove this assumption.

However, if Figure 9 is compared to Figure 10, it can readily be seen that the slip surface would probably follow such a path at least on an intuitive basis. Of course, this prediction would be valid only for shallow anchors in dense sand or stiff, silty clay. In loose sand or soft clay, the shape of the slip surface would probably be a vertical or near-vertical surface around the edge of the anchor.

---

44 R. J. Taylor *et al.*, *Direct Embedment Anchor Holding Capacity*, Technical Note N-1245, Naval Civil Engineering Laboratory, Port Hueneme, California, December 1972, p. 17.

45 *Ibid.*, p. 18.

46 *Ibid.*, pp. 12-15.

APPENDIX

BREAKOUT RESISTANCE CONTROLLING FACTORS

The following is an extract from Aleksandar S. Vesic's report: "Breakout Resistance of Objects Embedded in Ocean Bottom," September, 1971.[47] As the title states, this report concerns the extraction of buried objects from the ocean bottom:

"There are a number of controlling factors which must be determined and evaluated before the breakout resistance for an object (anchor) can be predicted. These are derived as follows:

"The effective weight of an anchor can be determined easily using the following equation:

$$\overline{W} = W - U$$

wherein, W equals the object's (anchor's) total weight in air and the buoyancy in water, U. The effective weight of the involved sediment can readily be obtained if the effective unit weight, γ', and the volume of the body of sediment are known. For the effective unit weight γ', the equation

$$\gamma' = \frac{(G_s - 1)\ 2w}{1 + e}$$

can be used in which G_s = the specific gravity of the sediment; 2w = unit weight of water; and e = the void ratio of the sediment. For saturated sediment the latter quantity is equal to $e = wG_s$ in which w = the water content of the sediment. In the case of marine and fluvial sediments it would be natural to expect a saturated condition.

"Should there be a steady vertical seepage of gradient i in the sediment under observation, the apparent sediment weight will be changed to $\gamma'' = \gamma' \pm \gamma w^i$ in which the plus sign means downward and the minus means upward flow of water.

"In determining the volume of sediment involved in extraction, it is necessary to know the exact shape of the slip surface in the sediment.

---

[47] Published in *Journal of Soil Mechanics and Foundation Division*, ASCE, Vol. 97, No. SM9, Proc. Paper 8372.

"The shape of this surface has been the object of extensive speculation in the past, mostly in connection with analysis of footings of transmission towers subjected to vertical pull-out forces. On the basis of experiments on model anchor plates in dense sand, as well as from some theoretical conditions, Balta suggested that the slip surface for circular buried objects should be part of a torus, with a generatrix consisting of a circle (Figure 10). The circle should meet the sediment surface at statically correct angle $\theta_0 = 45° - \phi/2$ and the plate edge at kinematically correct angle $\theta = 90°$.

"Observations in small scale model tests with anchor plates and anchor piles at Duke University proved that the shape shown in Figure 10 occurs only in the case of relatively shallow anchors in dense sand or stiff silty clay. For shallow anchors in loose sand or soft clay, the slip surface, though not clearly established, is closer to being a vertical cylinder around the perimeter of the anchor. This suggests that the shape of the slip surface is a function of the density or stiffness of the sediment mass involved.

"Thus, for objects embedded in loose and compressible sediments, it is more reasonable to assume that the sediment involved in extraction is essentially only the sediment immediately above the object.

"This may also be proved to be a reasonable assumption in any case when the sediment immediately surrounding the object is weakened by remolding. At the same time, the assumption of a toroidal slip surface (such as 01 in Figure 10) will yield the maximum possible effective weight of the involved sediment mass.

"It may be added that the difference between the sediment weight for an assumed toroidal slip surface, as compared with an assumed cylindrical slip surface is small for relatively shallow and long objects. However the difference can be very significant for circular objects at greater depth.

"Note that very deep anchors do not fail in general shear failure such as that shown in Figure 10, regardless of the *relative density* of the soil. Experiments indicate that they can be moved vertically for considerable distances by producing a failure pattern similar to punching shear failure in deep foundations. Only after being pulled up to relatively shallow depths may they eventually produce general shear failures such as that shown in Figure 10. This is demonstrated in Figure 11.

"The critical relative depth, D/B, above which embedded objects should behave as shallow anchors depends on the relative density of the sediments and possibly some other yet unclarified factors. Available experimental evidence using 3-in. dia. plates suggests that this limiting depth, D/B, in sand may increase from perhaps 2 for a very loose deposit to over 10 in a very dense deposit. In very soft bentonite clay the limit is at about D/B = 2, while in a stiff clay it appears to be around D/B = 5.

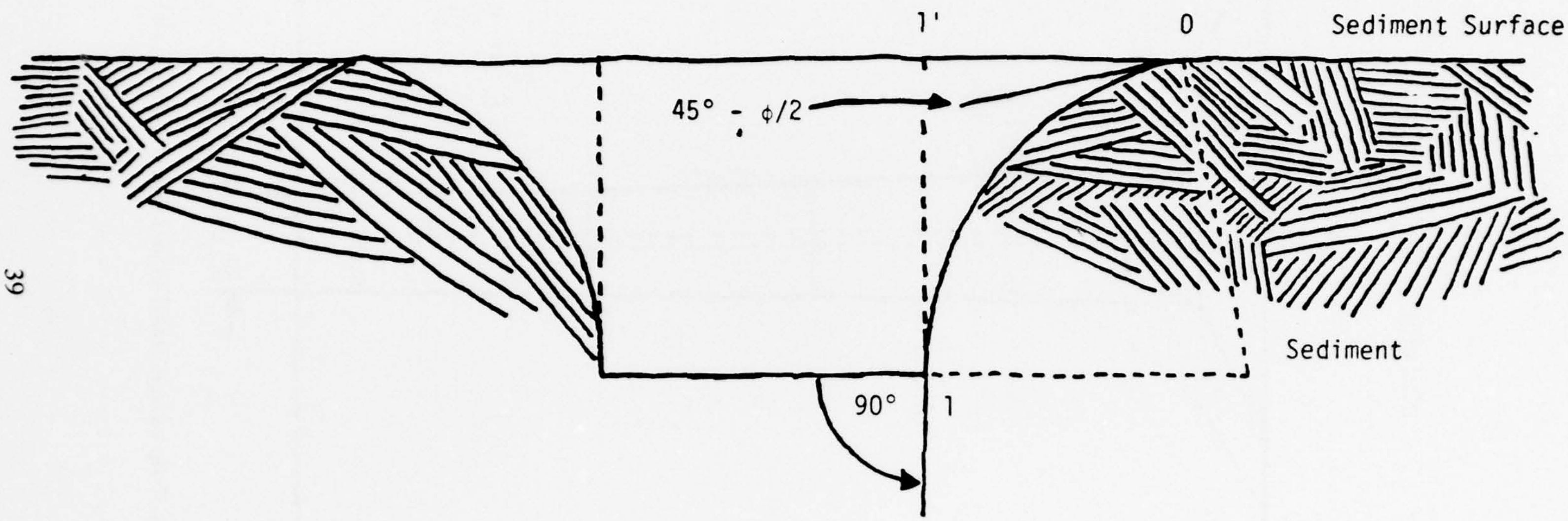


Figure 10. Shape of slip surface for circular buried objects.

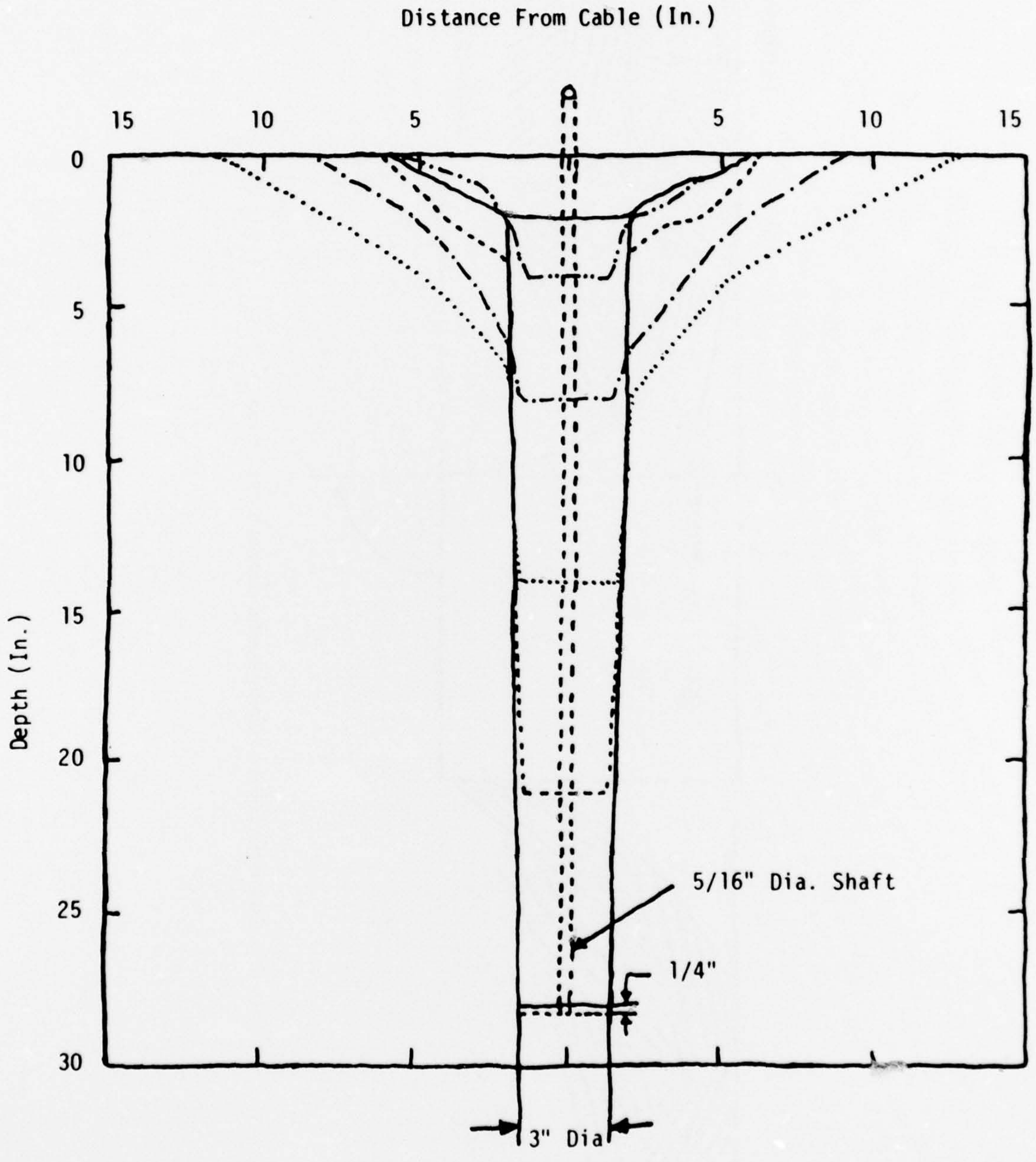


Figure 11. Observed shapes of slip surfaces caused by withdrawal of circular plates from stiff silty clay.

"In measuring and studying sediment strength, the effects of sediment remolding must be considered. Remolding occurs when sediment has been disturbed and weakened by the movement of the sediment, as would be the case in the deployment of an embedment anchor.

"It is known that most cohesive sediments lose a portion of their strength on remolding. Left to rest after that, they regain part or all of that strength by a regeneration process known as thixotropic regain. Computation of breakout forces should be based on estimated sediment strength at the time of attempted breakout. This strength will generally be different from undisturbed strength determined by appropriate in situ or laboratory tests. The sediment zones remolded by the deployment of an embedment anchor into the ocean bottom are zones of weakness, which may considerably alter the shape of slip surfaces in the sediment during extraction.

"Cohesive sediments containing active minerals will develop adhesion in contact with almost any material. The process is of a physico-chemical nature and it requires some time.

"Experiences with steel, concrete, and wood piles seem to indicate that, at least in soft sediments, the adhesion equals or exceeds the undrained shear strength after a period of a few days to, perhaps, 6 months. Little is known about the development of adhesion within the first hours or days after the objects have been brought into contact with sediment.

"Note that the development of adhesion is parallel to the process of regeneration of the shear strength of sediments. Comparative studies of the development of both with time for at least some sediment types and object materials would be highly desirable.

"Most of the known adhesion studies were concerned with measurements of resistance to shear. However in the breakout (extraction) problem, resistance to tension between the buried object and the underlying sediment must also be dealt with. Very little, if anything, is known about such a force, except that it exists.

"Penetration of an object through ocean bottom sediment before coming to rest causes some excess total stresses underneath, which may be taken mostly to be excess pore-water stresses. If the object has been resting at the bottom for a sufficiently long time, at least a portion of pre-water stresses may have dissipated.

"After application of an extraction force the overburden sediment immediately above the object is heavily compressed, while the underlying sediment is relieved from stress. Unless the sediment is so highly pervious as to respond immediately to stress changes, there will be an increase of pore-water stresses below the object. The difference results in a suction force.

"Very little is known about this force in any general sense. The measurements in the Duke tests with 3-in. dia. plate anchors indicate an average suction pressure of 2.8 psi. This pressure is significantly higher than the measure adhesion of 0.5 psi between this sediment and the anchor plate. (Note that the indicated value was measured with plate on sediment surface and that the suction pressure at some depth might be still higher.)

"A possible way of analyzing the suction pressure is given in Figure 12. If the initial stress condition, σ_i and U_i, above and below the objects, as well as total stress increments $\Delta\sigma$ imposed by object withdrawal are known, the pore pressure increments, Δu, can be determined by appropriate tests on undisturbed sediment samples. Recent research on yield behavior of sediments at Duke also offers the possibility of predetermining these pore-water increments analytically if the basic strength characteristic, c (soil adhesion) and ϕ' (angle of shearing resistance), of the sediment are known. In either case the difference in pore-pressure increments on the two sides of the objects represents the maximum possible suction pressure, which would occur whenever the rate of load application is much faster than the rate of dissipation of pore-water stresses.

"To find the breakout time in the situation where a known sustained load is applied, the needed solution could possibly be developed by using the three-dimensional theory of consolidation.

"It should be observed that the solutions of this kind could be used only as long as the liquidity index of the sediment is low enough so that no significant flow of sediment itself occurs toward the potential cavity formed under the object. Possible approaches for liquid sediments must be basically different, because of the dissimilarity in the physical properties between liquid sediments and sediments with low liquid indices.

"The preceding analyses are, in principle, applicable to the computation of extraction force in sediments which possess some finite shearing strength. These include, theoretically, all cohesionless sediments, such as sand, as well as cohesive sediments, such as clay, at water contents below the liquid limit. However, sediments at water contents above the liquid limit have practically no residual shear strength, at least when remolded or sheared at large strains. For such sediments a fundamentally different approach to the analysis of extraction force should be attempted; they should be treated as viscous fluids of appropriate rheological characteristics.

"The implementation of this approach to solution of the extraction force problem would require extensive basic studies of rheological behavior of sediment pastes. Such an approach should, in all probability, be simpler than the approach for plastic sediments outlined in the preceding paragraphs. Its main advantage may lie in the direct way in which the effects of time on extraction force can be introduced.

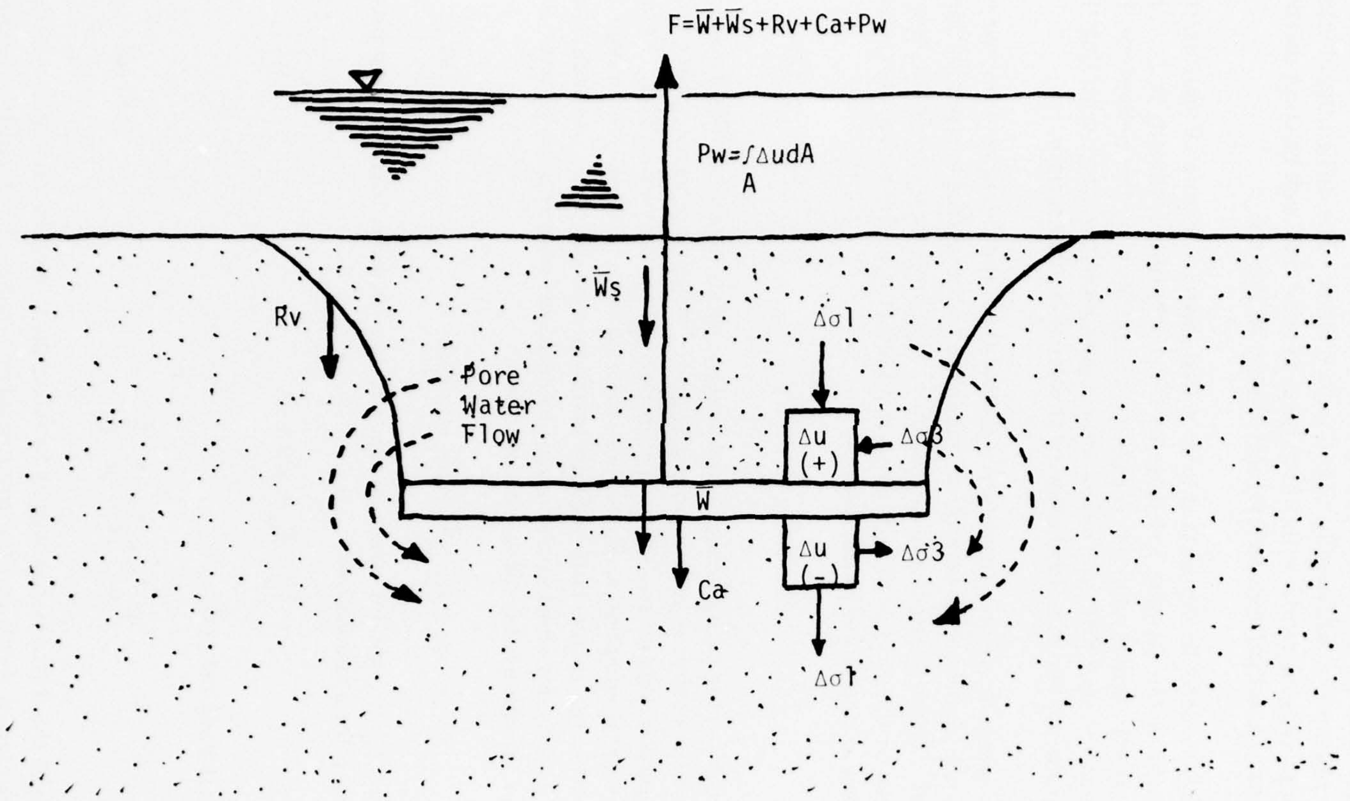


Figure 12. Analysis of suction force as pore-water stress difference problem.

"Should this rheological approach indeed prove as promising as it appears, an attempt should also be made to investigate the possibility of extending the range of its application to plastic sediments of sufficiently high liquidity index. The difficulties in using a more complex rheological model with this purpose in mind may well be compensated by the advantages of a unified approach for all cohesive sediments.

"In all cases where a definite slip surface such as that shown in Figure 10 appears, the vertical component of the shearing resistance of the overburden sediment, R_v, can be determined by an appropriate analysis. A rigorous computation by the methods of the theory of plasticity is very difficult, unless some assumptions are made regarding the shape of the slip surface and the distribution of stresses along that surface.

"An analytical approach to this problem is available from the solutions proposed by Vesic et al. for the problem of expansion cavities close to the surface of a semi-infinite rigid-plastic solid. These solutions give the ultimate radial pressure q_o needed to breakout a cylindrical or spherical cavity of radius R placed at depth D below the surface of the solid. They are presented in the form

$$q_o = cF_c + \gamma DF_q \qquad \text{(a)}$$

in which F_c and F_q = the cavity breakthrough factors, which depend on the shape and relative depth of the cavity, as well as on the angle of shearing resistance of the sediment. These solutions can be applied to the problem of anchor plates. They contain essentially the vertical component, R_v, of the sediment resistance, plus the weight of the sediment above the cavity, both reduced to the area of the plate. As such, they could be used directly for embedded spheres or embedded horizontal cylinders. For embedded plates, equation (a) is corrected and yields

$$q_o = R_v + W_s = c\bar{F}_c + \gamma D\bar{F}_q \qquad \text{(b)}$$

in which F_c and F_q = plate breakout factors. It can be shown that, for any plate, $F_e = F_c$. However, for a circular plate:

$$\bar{F}_q = F_q + 1/3\ B/D \qquad \text{(c)}$$

while for a long rectangular plate:

$$F_q{}' = F_q{}' + \frac{\pi}{8}\ \frac{B}{D} \qquad \text{(d)}$$

"For other shapes the difference in weight between the volume of the object protruding above its maximum width and the corresponding volume of overburden sediment

may be included, if significant. It should be emphasized that equations (a) or (b) include both R_v and W_s reduced to the maximum area of the embedded object, measured perpendicularly to the applied extraction force F. The magnitude of factor $F_c' = \bar{F}_c'$, F_q', and F_q' for long rectangular anchors are given in Table 8.

Table 8. Factors for Horizontal Cylinder and Long Rectangular Plate Breakout (Extraction)

ϕ, In Degrees (1)	D/B 0.5 (2)	1.0 (3)	1.5 (4)	2.5 (5)	5.0 (6)
0	0.81	1.61	2.42	4.04	8.07
	0.21	0.61	0.74	0.84	0.92
	1.00	1.00	1.00	1.00	1.00
10	0.84	1.68	2.52	4.22	8.43
	0.30	0.77	0.99	1.26	1.75
	1.09	1.16	1.25	1.42	1.83
20	0.84	1.67	2.52	4.19	8.37
	0.38	0.94	1.23	1.67	2.57
	1.17	1.33	1.49	1.83	2.65
30	0.79	1.58	2.37	3.99	7.89
	0.45	1.08	1.45	2.03	3.30
	1.24	1.47	1.71	2.19	3.38
40	0.70	1.40	2.11	3.51	7.02
	0.51	1.19	1.61	2.30	3.83
	1.30	1.58	1.87	2.46	3.91
50	0.58	1.17	1.75	2.92	5.84
	0.53	1.25	1.70	2.44	4.12
	1.32	2.04	1.96	2.60	4.20

First number $F'_c = F'_c$; second number F'_q (cylinder); and third number F'_q (long rectangular plate).

"A somewhat different approach to the problem of sediment resistance in extraction has been attempted by Muga (1967, 1968). He had developed a numerical procedure, based on the discrete-element model introduced by Harper and Ang (1963), for analytical determination of the extra action force. The sediment in this analysis is assumed to behave as a homogeneous elastic, perfectly plastic solid, following the Huber-Mises yield criterion in the plastic state.

"A good agreement between the results of this analysis and the experimental data from the San Francisco Bay was reported at least for the sediment in question, a highly plastic clay. In view of the yield criterion used it should not be expected that the analytical method could be applied to other types of sediment. An adaptation of the same procedure to other yield criteria, in particular to Coulomb-Mohr's, is possible, and should be attempted."

GLOSSARY OF TERMS

Adhesion – The force of attraction between unlike molecules.

Angle of Internal Friction – The angle included between the line of action of the force and a normal to the surfaces in contact. The body will not move unless this angle exceeds a certain value which depends upon the surfaces and substances involved (also called the angle of repose).

Angle of Shearing Resistance – See angle of internal friction above.

Breakout Force – The amount of force required to pull out (extract) an anchor from a sediment mass.

Cohesion – The force of attraction between like molecules.

Cohesionless Sediments – Those sediments which exhibit little or no cohesion, i.e., sands, gravel, and some silts.

Cohesive Sediments – Those sediments which display cohesion, i.e., mud, clays, and some silts.

Creep – The gradual movement of sediment resulting from the continued application of stress.

Disturbed Sediment – Sediment in which the grain orientation, gradation, amount of pore water, degree of consolidation, etc. have been modified by movement of the sediment mass; i.e., the penetration by an embedment anchor would result in the disruption of the original characteristics of the sediment mass.

Explosive Embedment Anchor (EEA) – An anchor which is propelled directly into the bottom sediments by means of a gun and derives its holding power by resistance of the projectile to the load.

Extraction Force – See breakout force.

Fluvial Sediments – Sediments derived from the action of rivers and streams.

Generatrix – An element generating a figure.

Holding Capacity – The maximum amount of force that an anchor can hold without being extracted (also called holding power).

In Situ – In its original place.

Key – The turning of an embedment anchor projectile to a position which is perpendicular to the direction of the load. This is usually roughly parallel to the sediment surface and at some depth below the seafloor, depending on the sediment type.

Kinematically – Derived from the study of motion alone without reference to the masses or forces involved.

Marine Sediments – Sediments derived directly or indirectly from marine erosional and depositional processes.

Pore Water – That water which occupies the spaces among the grains in a sediment mass.

Pore Water Pressure – The amount of pressure resulting from varying amounts of water occupying the void space in a given sediment mass.

Punching Shear Failure – In the case of the extraction of deeply embedded anchor plates, this refers to the fact that the shearing surface is perpendicular to the periphery of the plate and that the sediment being lifted is that which is directly above the plate.

Remolding – Is the process by which a sediment mass is disrupted by movement or penetration.

Repeated (Cyclic) Loading – The intermittent application of a load on an anchor.

Rheological – Derived from the study of the deformation and flow of matter.

Sediment – Material derived via the processes of weathering, erosion, transportation, and deposition; i.e., sand, gravel, boulders, silt, clay, mud, etc.

Seepage – The slow movement of pore water from above an anchor plate to the area below the plate.

Soil – Material formed either directly from the weathering of the local bedrock and or from the incorporation of sediment that has been moved from its place of origin.

Thixotropic Regain – A regenerative process in which a remolded sediment when left to rest regains all or part its original strength.

Torical – Characterized by a doughnut-shaped surface generated by the revolution of a conic, especially a circle, about an exterior line lying in its plane or having the shape of the solid enclosed by such as surface (also called an anchor ring).

Void Ratio – The ratio of the total porosity to the bulk volume of the sediment mass.

DISTRIBUTION FOR MERADCOM REPORT 2195

No. Copies	Addressee
	Department of Defense
1	Director, Technical Information Defense Advanced Research Projects Agency 1400 Wilson Blvd Arlington, VA 22209
1	Director Defense Nuclear Agency ATTN: STTL Washington, DC 20305
12	Defense Documentation Center Cameron Station Alexandria, VA 22314
	Department of the Army
6	Commander US Army Materiel Development and Readiness Command ATTN: DRCRD-WB DRCRD-T DRCRD-J DRCRD-O DRCRD-G DRCRD-FP 5001 Eisenhower Ave Alexandria, VA 22333
1	Commander, HQ TRADOC ATTN: ATEN-ME Fort Monroe, VA 23651
1	HQDA (DAMA-AOA-M) Washington, DC 20310
1	HQDA (DALO-TS M-P) Washington, DC 20310
1	HQDA (DAEN-RDL) Washington, DC 20314
1	HQDA (DAEN-MCE-D) Washington, DC 20314
1	Commander US Army Missile Research & Development Command ATTN: DRSMI-RR Redstone Arsenal, AL 35809
1	Chief. Engineer Division DCSLOG ATTN: AFKC-LG-E HQ Sixth US Army Presidio of San Francisco, CA 94129
1	Director Army Materials and Mechanics Research Center ATTN: DRXMR-STL Technical Library Watertown, MA 02172
1	US Army Ballistic Research Laboratories Technical Library DRXBR-LB (Bldg 305) Aberdeen Proving Ground, MD 21005
1	Commander Edgewood Arsenal ATTN: SAREA-TS-L Aberdeen Proving Ground, MD 21010
1	Commander US Army Aberdeen Proving Ground ATTN: STEAP-MT-U (GE Branch) Aberdeen Proving Ground, MD 21005
1	Director US Army Materiel Systems Analysis Agency ATTN: DRXSY-CM Aberdeen Proving Ground, MD 21005
1	Director US Army Engineer Waterways Experiment Station ATTN: Chief, Library Branch Technical Information Center Vicksburg, MS 39180
1	Commander Picatinny Arsenal ATTN: SARPA-TS-S No. 59 Dover, NJ 07801
1	Commander US Army Troop Support & Aviation Materiel Readiness Command ATTN: DRSTS-KTE 4300 Goodfellow Blvd St. Louis, MO 63120

No. Copies	Addressee
2	Director Petrol & Fld Svc Dept US Army Quartermaster School Fort Lee, VA 23801
1	Commander US Army Electronics Research & Development Command ATTN: DRSEL-GG-TD Fort Monmouth, NJ 07703
1	President US Army Aviation Test Board ATTN: STEBG-PO Fort Rucker, AL 36360
1	US Army Aviation School Library P.O. Drawer 0 Fort Rucker, AL 36360
1	HQ, 193D Infantry Brigade (CZ) Directorate of Facilities Engineering Fort Amador, Canal Zone
1	Commander Special Forces Detachment (Airborne), Europe APO New York 09050
1	HQ, USAREUR & Seventh Army DCSENGR, ATTN: AEAEN-MO ATTN: Mil Ops Div APO New York 09403
2	Engineer Representative US Army Standardization Group, UK Box 65, FPO New York 09510
1	Commander Rock Island Arsenal ATTN: SARRI-LPL Rock Island, IL 61201
1	Plastics Technical Evaluation Center Picatinny Arsenal, Bldg 176 ATTN: A. M. Anzalone SARPA-FR-M-D Dover, NJ 07801
1	Commander Frankford Arsenal ATTN: Library, K2400, B1 51-2 Philadelphia, PA 19137

No. Copies	Addressee
1	Learning Resources Center US Army Engineer School Bldg 270 Fort Belvoir, VA 22060
1	President US Army Airborne, Communications & Electronics ATTN: STEBF-ABTD Fort Bragg, NC 28307
1	Commander Headquarters, 39th Engineer Battalion (Cbt) Fort Devens, MA 01433
1	President US Army Armor and Engineer Board ATTN: ATZK-AE-TD-E Fort Knox, KY 40121
1	Commandant US Army Command and General Staff College ATTN: ATSW-RI-L Fort Leavenworth, KS 66027
1	Commander 2nd Engineer Group ATTN: S4 APO San Francisco 96301
1	Commander and Director USAFESA ATTN: FESA-RTD Fort Belvoir, VA 22060
	MERADCOM
1	Commander Technical Director Assoc Tech Dir/R&D Assoc Tech Dir/Engrg & Acq Assoc Tech Dir/Matl Asmt Assoc Tech Dir/Tech Asmt CIRCULATE
1	Chief, Countermine Lab Chief, Electrical Power Lab Chief, Camouflage & Topo Lab Chief, Marine & Bridge Lab Chief, Mech & Const Eqpt Lab Chief, Counter Intrusion Lab Chief, Product Assur & Testing Lab Chief, Material Technology Lab Chief, TARSO CIRCULATE

No. Copies	Addressee
2	Energy & Water Resources Lab
10	Fuels Handling Eqpt Div
3	Tech Reports Ofc
3	Security Ofc
2	Tech Library
1	Requirements & Programs Ofc
1	Information Ofc
1	Ofc of Counsel
	Department of the Navy
1	Director, Physics Program (421) Office of Naval Research Arlington, VA 22217
1	Director Naval Research Laboratory ATTN: Code 2627 Washington, DC 20375
1	Commander, Naval Facilities Engineering Command Department of the Navy ATTN: Code 032-A 200 Stovall St Alexandria, VA 22332
1	US Naval Oceanographic Office Library (Code 1600) Washington, DC 20373
1	Officer-in-Charge (Code L31) Civil Engineering Laboratory Naval Construction Battalion Cntr Port Hueneme, CA 93043
1	Director Earth Physics Program Code 463 Office of Naval Research Arlington, VA 22217
	Department of the Air Force
1	HQ USAF/RDPS (Mr. Allan Eaffy) Washington, DC 20330
1	Mr. William J. Engle Chief, Utilities Branch HQ USAF/PREEU Washington, DC 20332
1	AFSC/INJ Andrews AFB, MD 20334

No. Copies	Addressee
1	OL-AA AFCEC/DEZ Kirtland AFB, NM 87117
1	AFCEC/XR/21 Tyndall AFB, FL 32401
1	HQ USAF/PREES ATTN: Mr. Edwin B. Mixon Bolling AFB-Bldg 626 Washington, DC 20332
1	AFAPL/SFL Wright-Patterson AFB, OH 45433
1	ASD/ENCSP Wright-Patterson AFB, OH 45433
1	Department of Transportation Library, FOB 10A, TAD-494.6 800 Independence Ave., SW Washington, DC 20591
	Others
1	Professor Raymond R. Fox School of Engineering and Applied Science The George Washington University Washington, DC 20052

1 2 3 73,436 — AG — Ft Belvoir